第 28 卷 第 4 期
2007 年 4 月

半 导 体 学 报
CHINESE JOURNAL OF SEMICONDUCTORS

Vol.28 No.4
Apr.,2007

Effect of Inertial Shock on RF MEMS Capacitive Switches Property in Low Vacuum*

Dong Linxi†, Sun Lingling, and Xu Xiaoliang

(*Institute of Microelectronics CAD, Hangzhou Dianzi University, Hangzhou* 310018, *China*)

Abstract: The influence of outside inertial shock combined with RF signal voltages on the properties of a shunt capacitive MEMS switch encapsulated in a low vacuum environment is analyzed considering the damping of the air around the MEMS switch membrane. An analytical expression that approximately computes the displacement induced by outside shock is obtained. According to the expression, the minimum required mechanical stiffness constant of an MEMS switch beam in some maximum tolerated insertion loss condition and some external inertial shock environment or the insertion loss induced by external inertial shock can also be obtained. The influence is also illustrated with an RF MEMS capacitive switch example, which shows that outside environment factors have to be taken into account when designing RF MEMS capacitive switches working in low vacuum. While encapsulating RF MEMS switches in low vacuum diminishes the air damping and improves the switch speed and operation voltage, the performances of a switch is incident to being influenced by outside environment. This study is very useful for the optimized design of RF MEMS capacitive switches working in low vacuum.

Key words: reliable operation condition; RF MEMS switch; low vacuum; mechanical shock; air damping
EEACC: 2180B
CLC number: TN4 **Document code**: A **Article ID**: 0253-4177(2007)04-0507-07

1 Introduction

Microelectromechanical systems (MEMS) technology is on the verge of revolutionizing radio frequency (RF) and microwave applications. RF MEMS switches have been extensively studied during the last decade[1~3] for many applications, including signal routing in transmission and reception applications, impedance matching networks, and wideband tuning networks.

Shunt capacitive RF MEMS switches, as shown in Fig. 1, may be one of the most extensively studied switches since they are also used in phase shifting and time delay circuits, such as in phased-array radars and communications antennas, and also since they have the advantages of low insertion loss, high isolation, low return loss, low cost, and low power consumption compared to traditional semiconductor implementations (such as FETs or pin diodes). But capacitive switches also have a number of drawbacks, such as relatively high bias voltage in the case of electrostatic actuation[4], stiction[5] and dielectric charging[6]. To solve these problems, encapsulating MEMS switches in low vacuum environment is one of the most useful methods, which reduces the air damping effect of the structures. Nevertheless, RF MEMS switches in low vacuum packaging may be incident to being influenced by outside inertial shock. Therefore, the investigation of the influence of outside inertial shock on MEMS switch performance is of great importance for the design considerations of RF MEMS switches.

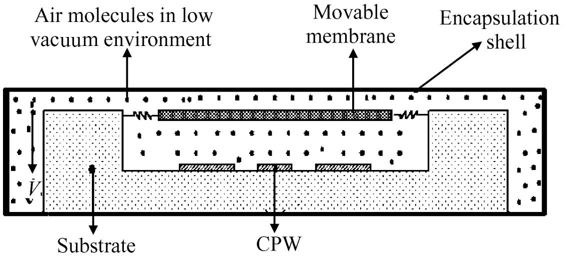

Fig. 1 Schematic cross-section of a capacitive switch in low vacuum

In this paper, the effects of outside inertial

---

* Project supported by the National Natural Science Foundation of China (No. 60506015) and the Scientific Research Fund of the Zhejiang Provincial Education Department

† Corresponding author. Email: phddong_lx@yahoo.com.cn

Received 16 October 2006, revised manuscript received 16 November 2006

shock on RF MEMS switches are investigated by the conservation of energy and the kinetic energy theorem considering the air damping around RF switch membrane working in a low vacuum environment. An approximate energy balance equation of the shunt capacitive MEMS switch system is derived. By the investigated results in this paper, the minimum required mechanical stiffness constant of shunt capacitive RF MEMS switches encapsulated in low vacuum in some maximum tolerated insertion loss condition and some known mechanical shock environment or the insertion loss induced by external inertial shock can also be obtained. Thus the results will be of practical use for the optimized design of capacitive RF MEMS switches.

2 Insertion loss of a shunt capacitive RF MEMS switch

Because an RF MEMS switch is a symmetrical two-port network, the reflection coefficient can be computed by the following equation[7]:

$$S_{11} = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0} = \frac{A + BY_0 - C'Z_0 - D}{A + BY_0 + C'Z_0 + D} \quad (1)$$

Here A, B, C', D are the transmission parameters of the RF switch, Y_0 is the admittance, and Z_0 is the characteristic impedance of the transmission line. Therefore the reflection coefficient of a shunt capacitive RF MEMS switch is

$$S_{11} = \frac{V_1^-}{V_1^+} = \frac{1 + 0 \times Y_0 - \mathrm{j}\omega CZ_0 - 1}{1 + 0 \times Y_0 + \mathrm{j}\omega CZ_0 + 1} = -\frac{\mathrm{j}\omega CZ_0}{2 + \mathrm{j}\omega CZ_0} \quad (2)$$

where V_1^+ and V_1^- are the incident and reflected RF amplitude voltages on the t-line, respectively, ω is the operating frequency, and C is the capacitance of the RF MEMS switch.

For a shunt capacitive RF MEMS switch in the up-state, the amplitude voltage on the capacitor of the RF switch is

$$V_{\text{SW}} = V_1^- + V_1^+ = (S_{11} + 1)V_1^+ \quad (3)$$

For an incident RF signal of power P, the incident amplitude voltage on the t-line is $V_1^+ = \sqrt{2PZ_0}$. Substituting V_1^+ into Eq. (3), the rms voltage on the capacitor by the RF-power incident on the RF MEMS switch can be computed by

$$V_{\text{sw\_rms}} = |V_{\text{SW}}| = \left|\left(1 - \frac{\mathrm{j}\omega CZ_0}{2 + \mathrm{j}\omega CZ_0}\right)\sqrt{2PZ_0}\right| = \frac{\sqrt{Z_0 P}}{\sqrt{1 + \left(\frac{\omega CZ_0}{2}\right)^2}} = \frac{V_{\text{in\_rms}}}{\sqrt{1 + \left(\frac{\omega CZ_0}{2}\right)^2}} \quad (4)$$

where $V_{\text{in\_rms}} = \sqrt{Z_0 P}$ is the rms voltage of the incident RF signal.

The insertion loss (i. e. voltage transmission coefficient) of the shunt capacitive RF MEMS switch can be defined by

$$S_{12} = 20\lg\left(\frac{V_{\text{in\_rms}}}{V_{\text{sw\_rms}}}\right) = 20\lg\left(\sqrt{1 + \left(\frac{\omega CZ_0}{2}\right)^2}\right) \quad (5)$$

From Eq. (5), it can be gotten that the insertion loss of a capacitive switch is relative to the capacitance of the switch. If the MEMS switch in the up-state suffers from outside inertial shock, the capacitance of the RF MEMS switch will be changed, and the transmission efficiency of an RF signal through the MEMS switch will be influenced. If a shunt capacitive RF MEMS switch works in a low vacuum environment, the influence will be enlarged.

3 Air damping of a shunt capacitive RF MEMS switch in low vacuum

Air damping is usually the most important factor in determining the quality factor of MEMS devices. Therefore, to diminish the air damping, the MEMS devices are encapsulated in a housing where air pressure is in low vacuum ($p <$ 1000Pa). In this case, the quality factor is still mainly determined by the energy losses to the surrounding air molecules[8]. If a molecule before entering the RF MEMS switch microstructure has the velocity components of υ_{xz0} in the x-z plane and υ_{y0} in the y-direction, the extra kinetic energy gained by the molecule via collisions with the RF MEMS switch microstructure can be computed by the equation[9]

$$\Delta e_{\text{k}} = \frac{1}{2}m\left[\frac{2l\upsilon_{y0}^2}{(d_0 - y)\upsilon_{xz0}}\dot{y} + \frac{l^2\upsilon_{y0}^2}{(d_0 - y)^2\upsilon_{xz0}^2}\dot{y}^2\right] \quad (6)$$

where m is the mass of the gas molecule, l is the lateral travel distance under the switch, and y and $\dot{y}$ are the displacement and velocity of the MEMS switch microstructure induced by the outside inertial shock.

According to the Boltzmann statistics, the number of molecules moving across the boundary of the RF MEMS switch per unit time from outside to just under the moving switch microstructure is

$$n_{\text{num}} = L(d_0 - y)n_0\int_0^{\infty} f(\upsilon)\upsilon \mathrm{d}\upsilon \qquad (7)$$

where n_0 is the concentration of the molecules, and L is the peripheral length of the MEMS switch microstructure. $f(\upsilon) = \sqrt{m/2\pi kT}\mathrm{e}^{-m\upsilon^2/2kT}$ is substituted into Eq. (7), giving

$$n_{\text{num}} = L(d_0 - y)n_0\sqrt{\frac{kT}{2\pi m}} \qquad (8)$$

Since the molecules under the switch microstructure come from peripheral four planes, we define the average velocity of the molecules $\bar{\upsilon} = \sqrt{8kT/\pi m}$, and k is the Boltzmann constant, and T is the absolute temperature. Thus Equation (8) can be written as

$$n_{\text{num}} = \frac{1}{4}n_0\bar{\upsilon}L(d_0 - y) \qquad (9)$$

For simplicity, we express υ_{y0} and υ_{xz0} in Eq. (6) by the average velocity of the gas molecules, i.e. $\upsilon = \sqrt{3}\upsilon_{y0}$, $\upsilon_{xz0} = \sqrt{2}\upsilon_{y0}$. Therefore, the total energy loss of the RF MEMS switch microstructure to the gas molecules in the first quarter vibration cycle induced by outside inertial pulse shock is

$$\Delta E_{\text{qur\_air}} = \frac{1}{4}\rho_0\bar{\upsilon}L\frac{1}{\omega}\times$$

$$\int_0^{\frac{\pi}{2}}\left[\frac{l^2A_0^2\omega^2}{4(d_0 - y)}\cos^2\omega t + \frac{lA_0\omega\bar{\upsilon}}{\sqrt{6}}\cos\omega t\right]\mathrm{d}(\omega t) \qquad (10)$$

where $\rho_0 = n_0 m$ is the density of the gas, y is the displacement of the switch microstructure induced by the outside inertial shock at time t, and A_0 is the maximum displacement of the MEMS switch membrane in the first quarter vibration cycle. Suppose that the amplitude of the outside inertial pulse shock a is large enough and the duration of the shock Δt is so short that the velocity and the displacement of the seismic RF MEMS membrane at the end of the pulse is very small. Then the inertial pulse shock response of the RF MEMS switch encapsulated in low vacuum and whose air damping is small in the first quarter vibration cycle can be approximated as

$$y = y_1 e^{-\zeta t}\sin\omega_0 t \cong y_1\sin\omega_0 t, \quad 0 \leqslant t \leqslant T'/4 \qquad (11)$$

where ω_0 is the natural angle frequency of the RF MEMS switch, ζ is the damping coefficient, and $T' = 2\pi/\omega_0$. Thus the average energy loss of the RF MEMS switch microstructure in the first quarter vibration cycle is

$$\Delta E_{\text{qur\_air}} = \frac{1}{4}\rho_0\bar{\upsilon}L\frac{l^2 y_1^2\omega_0}{4d_0}\times$$

$$\left\{\begin{matrix}\sqrt{1-\bar{y}_1^2}(\pi/2+\bar{y}_1) + 2(-1+\bar{y}_1^2)\times \\ \left[\begin{matrix}\arctan(\bar{y}_1/\sqrt{1-\bar{y}_1^2}) - \\ \arctan((\bar{y}_1 - 1)/\sqrt{1-\bar{y}_1^2})\end{matrix}\right]\end{matrix}\right\}\times$$

$$\frac{1}{\bar{y}_1^2\sqrt{1-\bar{y}_1^2}} + \frac{1}{4}\rho_0\bar{\upsilon}^2L\frac{ly_1}{\sqrt{6}} \qquad (12)$$

where $\bar{y}_1 = y_1/d_0$, $y_1 = A_0$. To simplify the problem, we use the average value of l^2 and l, i.e. $l^2 = 2a_\text{p}b_\text{p}/\pi$[9], and a_p and b_p are the length and width of the switch microstructure. If the atmospheric pressure is P_{air} and the specific mass of gas corresponding to P_{air} is ρ_{air}, according to the ideal gas state equation, then the specific mass corresponding to pressure P is $\rho_0 = (\rho_{\text{air}}/P_{\text{air}})P$, and for $\rho_{\text{air}}/P_{\text{air}} = M_\text{m}/RT$, then $\rho_0 = (M_\text{m}/RT)P$, where M_m is the molar weight of the gas and R is the universal gas constant. Therefore the average energy loss to air damping in the first quarter vibration cycle induced by outside inertial pulse shock can be written as

$$\Delta E_{\text{qur\_air}} = \frac{1}{\sqrt{2\pi}}f_0(La_\text{p}b_\text{p}d_0)\sqrt{\frac{M_\text{m}}{RT}}P\times$$

$$\left\{\begin{matrix}\sqrt{1-\bar{y}_1^2}(\pi/2+\bar{r}) + 2(-1+\bar{y}_1^2)\times \\ \left[\begin{matrix}\arctan(\bar{y}_1/\sqrt{1-\bar{y}_1^2}) - \\ \arctan((\bar{y}_1 - 1)/\sqrt{1-\bar{y}_1^2})\end{matrix}\right]\end{matrix}\right\}\times$$

$$\frac{1}{\sqrt{1-\bar{y}_1^2}} + \frac{1}{\sqrt{3}\pi^{1.5}}(L\sqrt{4a_\text{p}b_\text{p}}d_0)P\bar{y}_1 \qquad (13)$$

where f_0 is the natural frequency of the RF MEMS switch.

4 Effect of mechanical shock on the capacitance of a capacitive RF MEMS switch

If the RF signal through the MEMS switch is V, the potential energy of the shunt capacitive switch can be computed by the following equation, where the energy is relative to the state of y equal to zero[8]:

$$E(y) = \frac{1}{2}ky^2 - \frac{1}{2}(C(y) - C_0)V^2 \qquad (14)$$

Here $C_0 = \varepsilon\varepsilon_0 A/d_0$, $C(y) = \varepsilon\varepsilon_0 A/d_0(1-\tilde{y})$, $\tilde{y} = y/d_0$, and k is the spring constant of the RF MEMS switch membrane. According to the defined notation, the above equation can also be written as

$$E(\tilde{y}) = \frac{1}{2}kd_0^2\tilde{y}^2 - \frac{1}{2}\times\frac{\varepsilon\varepsilon_0 A}{d_0}\times V^2\times\frac{\tilde{y}}{1-\tilde{y}} \tag{15}$$

With the notation $p = \varepsilon\varepsilon_0 AV^2/2d_0^2/kd_0 = F_{e0}/kd_0$, the normalized potential energy equation of the capacitive RF MEMS switch is

$$E(\tilde{y}) = \frac{1}{2}kd_0^2\left(\tilde{y}^2 - 2p\frac{\tilde{y}}{1-\tilde{y}}\right) \tag{16}$$

The initial potential energy of the MEMS switch is $E(\tilde{y}_0)$, where $\tilde{y}_0$ is the normalized displacement induced by the RF signal through the shunt capacitive switch, which is in the up-state in the condition that $\tilde{y}_0$ is smaller than the normalized pull-in location $\tilde{y}_{\max}$, which can be computed by the following equation:

$$\frac{\mathrm{d}E(\tilde{y})}{\mathrm{d}\tilde{y}} = \frac{1}{2}kd_0^2\left(2\tilde{y} - 2p\frac{1}{(1-\tilde{y})^2}\right) = 0 \tag{17}$$

We have the assumption that the amplitude of the outside inertial pulse shock a is large enough and the duration of the shock Δt ($\Delta t \ll \sqrt{2}/\omega_0$[10]) is so short that the velocity and the displacement of the seismic RF MEMS switch mass at the end of the pulse is small. Then the initial velocity condition can be gotten, and is found to be $\dot{y}_0 = a(\Delta t)$.

Therefore, if the maximum normalized displacement of the shunt capacitive RF MEMS switch microstructure induced by the outside inertial shock a is $\tilde{y}_1$, the energy balance equation of the MEMS switch system which works in low vacuum environment can be written as

$$\frac{1}{2}M_{\mathrm{p}}a^2(\Delta t)^2 = E(\tilde{y}_1) - E(\tilde{y}_0) + \Delta E_{\mathrm{qur\_air}} = \frac{1}{2}kd_0^2\left((\tilde{y}_1^2 - \tilde{y}_0^2) - 2p\frac{\tilde{y}_1 - \tilde{y}_0}{(1-\tilde{y}_1)(1-\tilde{y}_0)}\right) + \Delta E_{\mathrm{qur\_air}} \tag{18}$$

where M_{p} is the mass of the switch microstructure, and $\Delta E_{\mathrm{qur\_air}}$ is the average energy loss for air damping in low vacuum, as shown in Eq. (13). The above equation can also be written as

$$a(\Delta t) = \sqrt{(\omega_0 d_0)^2\left((\tilde{y}_1^2 - \tilde{y}_0^2) - 2p\frac{\tilde{y}_1 - \tilde{y}_0}{(1-\tilde{y}_1)(1-\tilde{y}_0)}\right) + \frac{2}{M_{\mathrm{p}}}\Delta E_{\mathrm{qur\_air}}} \tag{19}$$

Therefore, if a shunt capacitive RF MEMS switch whose dimensions have been known is shocked by an inertial pulse a whose duration time is Δt, the maximum normalized displacement $\tilde{y}_1$ ($<\tilde{y}_{\max}$) induced by the inertial shock can be computed according to Eq. (19), and thus the capacitance change of RF MEMS switches can also be obtained. Thus the effect of the change of up-state MEMS switch capacitance induced by the outside inertial shock on the insertion loss S_{12} can be found by Eq. (5).

5 Result and discussion

To show the effect of outside inertial environment on insertion loss of MEMS switches working in low vacuum, as an example, we analyze the capacitive shunt switch[11,12] whose dimension parameters and schematic cross-section are shown in Table 1 and Fig. 2, and which is assumed to be encapsulated in low vacuum to obtain sufficiently fast switch speed and decrease operation voltage. The air damping of the MEMS switch in low vacuum can be computed according to Eq. (13). When the switch is shocked by an inertial pulse, the maximum reliable operation displacement (i. e. pull-in happen) and initial displacement induced by RF signal of the MEMS switch which works at some radio frequency voltage can be computed by Eq. (17). The change values of capacitance of the MEMS switch in the conditions that the switch has the maximum tolerated insertion loss and is shocked by a different inertial pulse in a different vacuum extent can be computed by Eq. (19). According to these, the effects in different kinds of situations on the properties of the capacitive shunt switch are shown in Fig. 3～Fig. 6. For easy comparison with the analyzed results, we define the notation $\eta = a(\Delta t)/\omega_0 d_0$.

Table 1 Properties of the MEMS switch[11] under shock study

Parameter	Variable	Value
Gap in open state	d_0	1.5μm
Actuation area	A	107000μm^2
Mass of membrane	m	1.3μg
Spring constant	k	124N/m
Measured stiffness[12]	k_{test}	49N/m
Membrane length	a_{p}	332μm
Membrane width	b_{p}	332μm
Air pressure	P	≤1000Pa
Environment temperature	T	298K
Universal gas constant	R	8.3145

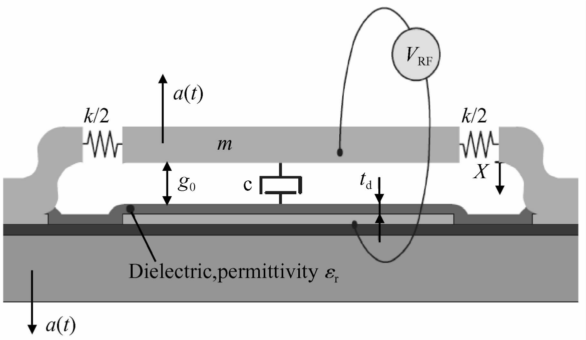

Fig. 2　Schematic section of the capacitive shunt switch[12]

From Fig. 3, it can be seen that the effect of an outside inertial shock pulse on the insertion loss is very evident. When outside inertial pulse increases from $\eta = 0.151$ to 0.971 (Δt is 0.1ms), the insertion loss changes from 0.1756 to 1.944dB if the air pressure is 1000Pa. When the air pressure reduces to 600Pa, the insertion loss changes from 0.1811 to 3.1024dB. Thus the effect of the extent of low vacuum of the air around the MEMS switch membrane on the insertion loss is also very evident. The damping of air in a low vacuum environment (≤1000Pa) around the switch plate must be considered when MEMS switches work in a badly inertial environment. From Fig. 4, it can be seen that the minimum stiffness constant increases from 73 to 476, 33 to 350, and 12.5 to 278N/m for maximum tolerated insertion losses of 0.5, 0.6, and 0.7dB at 2GHz and radio frequency signal voltage $V_{rf} = 2.5$V, respectively, when the MEMS switch is shocked by inertial pulse from 3400 to 5000m/s^2. If the air damping is not considered (i.e. in a very high vacuum environment), the minimum stiffness constant increases from 5.9 to 784, 624, and 531N/m for maximum tolerated insertion losses of 0.5, 0.6, and 0.7dB, respectively, when the shock pulse changes from 0 to 5000 m/s^2. Therefore, the air damping is very useful for the reliable operation of an MEMS capacitive switch, for example, the minimum stiffness constant of Coster's switch[11,12] working in low vacuum where air pressure is 1000Pa is 205N/m when the inertial pulse is 4000m/s^2 and radio frequency signal is 2GHz and $V_{rf} = 2.5$V for a maximum tolerated insertion loss 0.5dB, while the minimum constant of the switch increases to 444N/m if air damping is not considered.

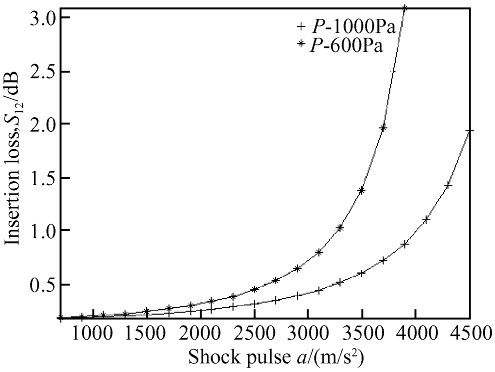

Fig. 3　Shock pulse and insertion loss

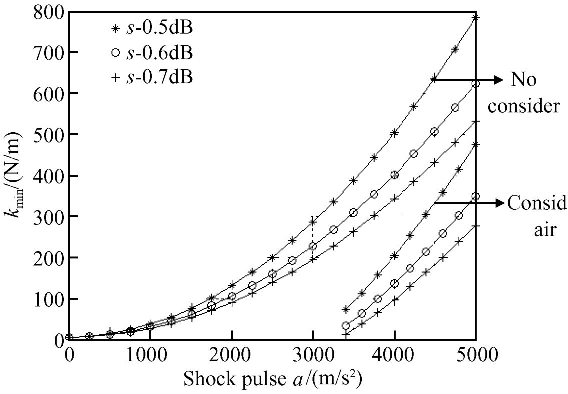

Fig. 4　Shock pulse and k_{min}

Figure 5 shows that the insertion loss of the switch increases from 0.7901 to 3.275dB at 2GHz if the air pressure of the working low vacuum environment of the switch is reduced from 1000 to 550Pa when the switch is shocked by an inertial pulse of 3800m/s^2 and 0.1ms duration time. If the duration time of the shock pulse increases to 0.12ms, the insertion loss will increase from 2.155 to 4.1868, even when air pressure only reduces from 1000 to 850Pa.

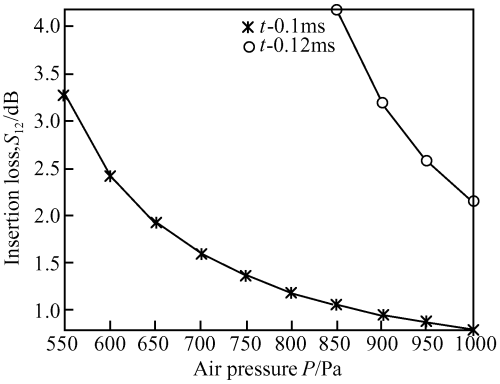

Fig. 5　Air pressure and insertion loss

According to Fig. 6, if the stiffness constant of an RF MEMS shunt switch is 49N/m, which is the same as the measured one of Costers' switch[11,12], and the maximum tolerated insertion loss of the shunt switch is 0.5dB, its power handling capability will be reduced by more than 90% when the working inertial environment of the MEMS switch is deteriorated from $a = 3100\mathrm{m/s^2}$ to $a_e = 3300\mathrm{m/s^2}$. When the air pressure is 1000Pa, the maximum tolerated RF voltage being handled decreases from 6.5 to 0.25V. If the maximum tolerated insertion loss of the switch is increased, the switch can endure a worse working environment.

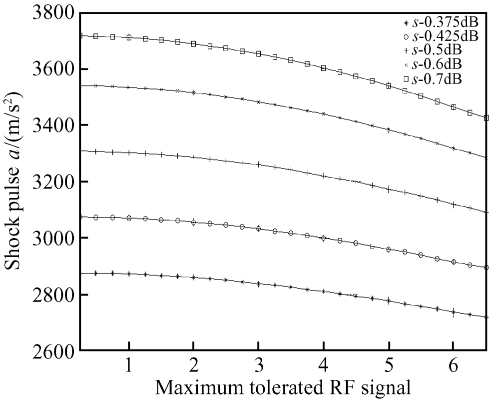

Fig.6 Power handle and shock pulse

Compared with the Coster's model, by which the fabricated MEMS switch can sustain shocks up to $3800\mathrm{m/s^2}$ when an RF signal of 2.5V is presented and the insertion loss is allowed to shift from its nominal value of 0.1～0.5dB at 2GHz, the device can only sustain shocks up to $3270\mathrm{m/s^2}$ in the same RF signal conditions according to the above low vacuum model when the air pressure is 1000Pa. This is because the low vacuum encapsulation significantly reduces the air damping compared with the situation of air atmosphere encapsulation.

In this analysis, instrumented acceleration tests typically report the load applied to the package rather than to the MEMS substrate. However, for purposes of analysis, we assume that the attachment mechanism (e.g., solder, adhesives) does not significantly alter the shape or intensity of the shock pulse[13], and while analyzing the effect of inertial shock using the energy conservation method, it is assumed that the energy of the shock signal is transmitted completely to the microstructure plate of the MEMS switch by the spring between the microstructure and the substrate. To simplify the problem, the above analyses have not considered the effect of the holes that are etched for etching the sacrificial layer and decreasing the air damping. Since the energy dissipation mechanism of the air in low vacuum is due to collision between air molecules and the microplate, the energy loss of the RF MEMS switch microstructure to the gas molecules in low vacuum can be approximately computed by Eq. (10) according to the size of the entity of the MEMS microstructure.

6 Conclusion

In this paper, the influence of the outside inertial shock combined with RF signal voltages on the properties of a shunt capacitive MEMS switch encapsulated in a low vacuum environment has been analyzed considering the damping of the air around the MEMS switch membrane. An analytical expression that approximately computes the displacement induced by outside shock is obtained. According to the expression, the minimum required mechanical stiffness constant of the MEMS switch beam in some maximum tolerated insertion loss condition and some external inertial shock environment or the insertion loss induced by external inertial shock can also be obtained. The influence is also illustrated with an RF MEMS capacitive switch example, which shows that outside environment factors have to be taken into account when designing RF MEMS capacitive switches working in low vacuum. For example, if the maximum tolerated insertion loss is 0.5dB, its power handling capability will fall by more than 90% if in a working environment in which the air pressure is 1000Pa and there is a $3300\mathrm{m/s^2}$ pulse shock; and when the outside inertial pulse increases from 700 to $4500\mathrm{m/s^2}$, the insertion loss increases from 0.1756 to 1.944dB if the air pressure is 1000Pa. The results also show that the air damping is very useful for the reliable operation of MEMS capacitive switches. For example, the minimum stiffness constant of the switch example when working in low vacuum in which the air pressure is 1000Pa is 205N/m when the inertial pulse is 4000m/s^2 and the radio frequency signal is 2GHz and V_{rf} = 2.5V for a maximum tolerated insertion loss of 0.5dB, whereas the minimum constant of the switch increases to 444N/m if air damping is not considered.

While encapsulating RF MEMS switches in low vacuum diminishes the air damping and improves the switch speed and operation voltage, the performance of switches is incident to being influenced by the outside environment. Therefore, this study is very useful for the optimized design of RF MEMS capacitive switches working in low vacuum.

References

[1] Tan G L, Rebeiz G M. A DC-contact MEMS shunt switch. IEEE Microw Wirel Compon Lett, 2002, 12: 212

[2] Peroulis D, Sarabandi K, Katehi L P B. Design of low actuation voltage RF MEMS switches. IEEE MTT-S Int Microwave Symp Digest, 2002: 165

[3] Rebeiz G M. RF MEMS: theory, design and technology. Hoboken, NJ: Wiley, 2003

[4] Pacheco S P, Katehi L P B, Nguyen C T C. Design of low actuation voltage RF MEMS switch. IEEE MTT-S, 2000: 165

[5] Van Spengen W M, Puers R, De Wolf I. A physical model to predict stiction in MEMS. J Micromech Microeng, 2002, 12: 702

[6] Reid J R. Simulation and measurement of dielectric charging in electrostatically actuated capacitive microwave switches. San Juan: MSM, 2002: 250

[7] Radmanesh M M. Radio frequency and microwave electronics illustrated. Beijing: Publishing House of Electronics Industry, 2002 (in Chinese) [Radmanesh M M. 射频与微波电子学. 北京：电子工业出版社，2002]

[8] Bao M. Micro mechanical transducers. In: Middelhoek S. Handbook of sensors and actuators. Amsterdam: Elsevier, 2000

[9] Bao M, Yang H, Yin H, et al. Energy transfer model for squeeze-film air damping in low vacuum. J Micromech Microeng, 2002, 12: 341

[10] Bao M H, Huang Y, Yang H, et al. Reliable operation conditions of capacitive inertial sensor for step and shock signals. Sensors Actuators A, 2004, 114: 41

[11] Steeneken P G, Rijks Th G S M, van Beek J T M, et al. Dynamics and squeeze film gas damping of a capacitive RF MEMS switch. J Micromech Microeng, 2005, 15: 176

[12] De Coster J, Tilmans H A C, Van Beek J T M, et al. The influence of mechanical shock on the operation of electrostatically driven RF-MEMS switches. J Micromech Microeng, 2004, 14: S49

[13] Srikar V T, Senturia S D. The reliability of microelectromechanical systems (MEMS) in shock environments. J Microelectromechan Syst, 2002, 11(3): 206

惯性冲击对低真空封装的 RF MEMS 电容开关性能的影响*

董林玺†　孙玲玲　徐小良

（杭州电子科技大学微电子 CAD 研究所，杭州　310018）

摘要： 分析了外界惯性冲击对低真空封装的旁路电容式 RF MEMS 开关性能的影响.得到了近似计算外界惯性冲击引起位移的解析式.在已知最大容许插入损耗和外部惯性冲击环境条件下，MEMS 开关支撑梁的最小机械刚度常数以及外部惯性冲击引起的插入损耗可以根据该式得到.通过 RF MEMS 电容式开关实例，表明设计低真空封装的 RF MEMS 电容式开关时应考虑外部环境因素.可见，RF MEMS 开关用低真空封装可以减小空气阻尼、改善开关速度和执行电压的同时，开关的性能却容易受外界环境因素的影响.该研究对低真空封装的 RF MEMS 电容式开关的优化设计很有意义.

关键词： 可靠操作条件；RF MEMS 开关；低真空；机械冲击；空气阻尼

EEACC： 2180B

中图分类号： TN4　　**文献标识码：** A　　**文章编号：** 0253-4177(2007)04-0507-07

---

* 国家自然科学基金(批准号：60506015)及浙江省教育局科学研究基金资助项目

† 通信作者. Email：phddong_lx@yahoo.com.cn

2006-10-16 收到，2006-11-16 定稿