

# RF MEMS Switches for Mobile Communication

by Peter Steeneken

## Introduction

The first widely used mechanically moving electrical switch was the telegraph key. On May 24, 1844, Samuel Morse opened an experimental telegraph line with a length of 40 miles by transmitting a message from Washington, D.C., to Baltimore. More than a century later, the transistor was discovered, which is currently, with a production volume exceeding the 10<sup>18</sup> devices per year,[1] without doubt the most widely spread electrical switch. The success of the transistor is mainly a result of its small dimensions, high switching speed and extremely low production costs (<10<sup>-6</sup> cents per transistor). Nevertheless there are some important aspects in which the “old-fashioned” mechanical switch performs better than the modern transistor. For example, its energy losses are lower because currents only run through low-resistance metals. Additionally, its linearity is better because Ohm’s law applies better to metals than to semiconductors.

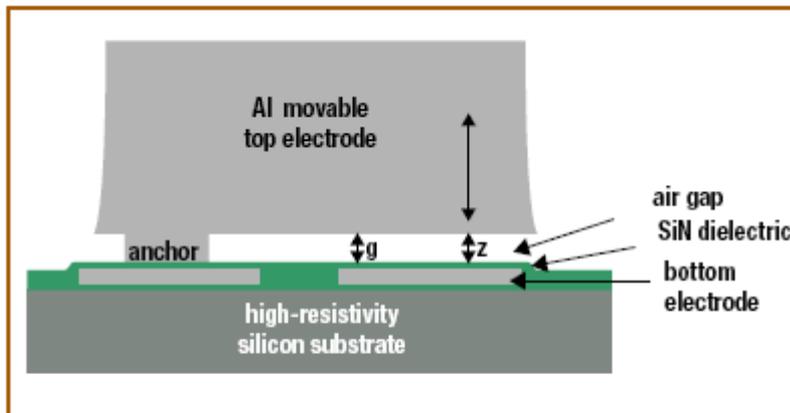


Figure 1. Cross Section of an RF MEMS-switch

These advantages can be of decisive importance for RF switches that are located close to the antenna of a mobile phone. Because RF powers are relatively high (~4W), it is important to minimize losses to save battery power. To prevent the mixing of frequencies, it is also essential to apply extremely linear devices. At NXP Semiconductors, work is in progress to combine the advantages of mechanically moving electrical switches with the miniaturization and low production costs of semiconductors. Such switches produced on a semiconductor substrate are called RF MEMS switches.

## Switches on Silicon

To facilitate the production of RF MEMS switches in an existing fab, we have chosen to base the technology on the NXP industrialized PASSITM process. This production process is dedicated to integrate capacitors and inductors on silicon. We have adapted this process to enable the production of RF MEMS switches. Figure 1 shows a cross section of a structure in this process. The gap  $g$  below the aluminum top electrode is created after deposition of the top electrode, by etching the “sacrificial” layer between the top electrode and the dielectric layer. This results in a released top electrode structure that can be moved by the electrostatic force. Figure 2 shows a scanning electron microscope (SEM) picture of such a switch. The top electrode is connected by eight springs to four anchor points. It is separated from the bottom electrode by a gap with thickness  $g$  and by a silicon nitride dielectric with thickness  $d_{diel}$ . The holes in the top electrode facilitate etching of the sacrificial layer and reduce the gas damping, thus resulting in faster switching.

## Mechanically Moving

## Forces

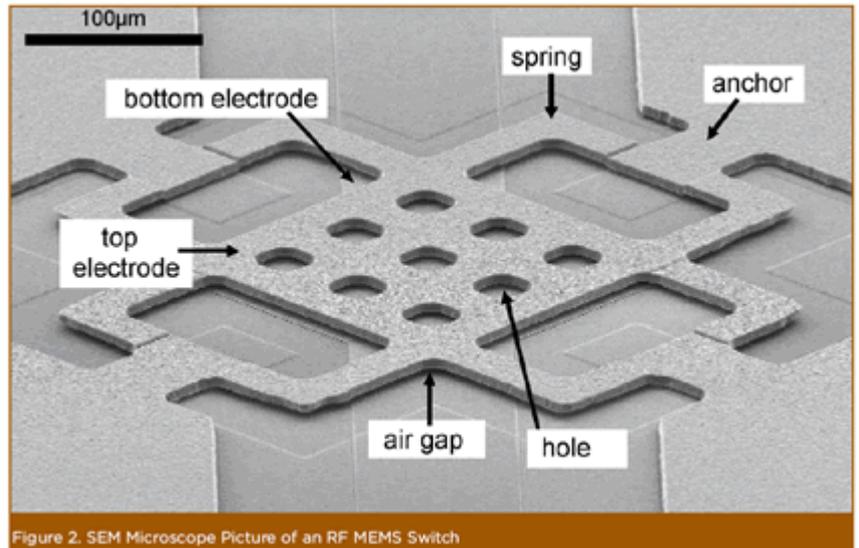
On a microscopic scale, other forces dominate than on a macroscopic scale. For example, gravity forces are proportional to the volume of a device, whereas electrostatic forces between parallel plate actuators remain equal if

all dimensions are reduced. This effect favors the application of electrostatic force actuation in microscopic devices.

For an accurate description of the motion of the top electrode of the RF MEMS switch, a thorough understanding of the dominant forces on this scale is essential. The four dominant forces in RF MEMS switches are:

1. Electrostatic force  $F_e$
2. Mechanical spring forces  $F_{spring}$
3. Contact forces  $F_c$
4. Air damping forces  $F_d$

These forces are shown in Figure 3. The equation of motion of the switch can be derived from one-dimensional approximations for the relevant forces.



This enables us to evaluate the static and dynamic motion of the switch and can be used to develop compact models of the switch[2,3] that can be implemented in circuit design software. Time-dependent capacitance measurements are used to study the dynamics of the switch.[2,4] For a more accurate calculation of the switching motion and the mechanical deformations in two or three dimensions, finite element models are used that solve the governing partial differential equations for an arbitrary structure.[5]

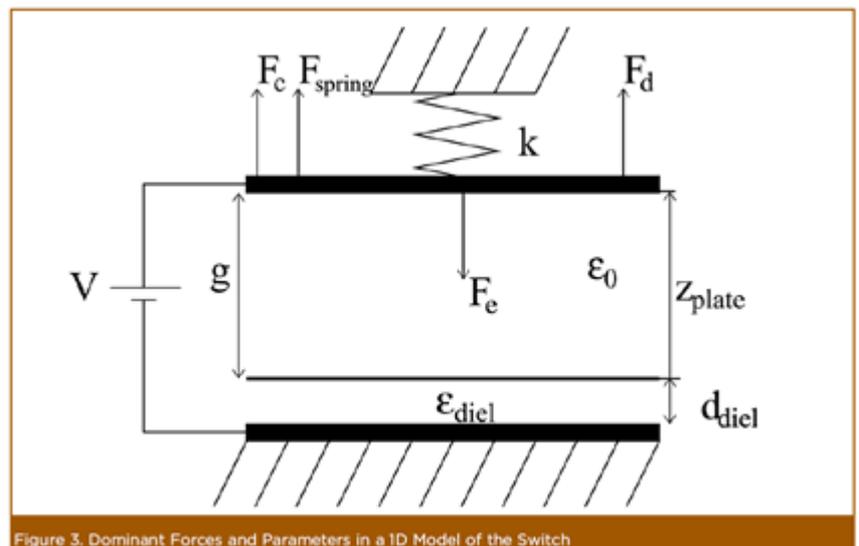
## Switching Action

The top electrode of the switch can be pulled downward by the electrostatic force that is generated when an actuation voltage is applied between the top and bottom electrodes. By gradually increasing this voltage and subsequently decreasing it, the switch will close and open. This results in a capacitance variation as shown in Figure 4. Closing and opening voltages are different because the electrostatic force depends both on the voltage and on the distance between the electrodes. At low voltages, the electrostatic forces are balanced by spring forces. At high voltages, the top electrode touches the dielectric layer and a balance exists between electrostatic, spring and contact forces.

In actual operation, the device will switch from an open (low actuation voltage) to a closed state (high actuation voltage), causing a change from a low to a high capacitance state. A corresponding reduction in the RF impedance will occur that enables the application of RF MEMS in switchable RF networks.

## Reliability

One of the biggest challenges that one faces when applying mechanical switches in mobile phones is to obtain a sufficiently high reliability. For certain applications the switch has to remain within specification limits for as



much as 10 years. There are three main mechanisms for failure of the switch: charge injection in the dielectric layer which can result in a change of the electrostatic forces, irreversible (plastic) deformation of the springs as a result of mechanical stresses; and degradation of the switch as a result of moisture between the electrodes.

Because it is practically unfeasible to test each switch for 10 years, deterministic reliability models that predict acceleration factors based on physics of failure are required. These models can provide an estimate of the lifetime of a switch from a short experiment.

Figure 5 shows an example of a measurement of the time-dependent charge injection into the silicon nitride dielectric.[4] Charge is injected into the dielectric as a result of the high-voltage ( $V_{\text{stress}}$ ). This charge generates an image charge in the top electrode and can thus influence the electrostatic force. Figure 5 shows a measurement of the voltage  $V_{\text{shift}}$  that is required to compensate this image charge as a function of stress time. The measurement shows that  $V_{\text{shift}}$  is proportional to the square root of the stress time  $t$  for values of  $V_{\text{stress}}$  between 30 and 47.5 V. Moreover, it appears that the rate of charge injection exponentially increases as a function of  $V_{\text{stress}}$ . With such measurements, the lifetime of the device under prolonged exposure to lower stress voltages can be estimated in a relatively short time.

## Application

Switches near the antenna of mobile phones require very low energy losses and a high linearity. RF MEMS switches typically have a resistance of only 0.2  $\Omega$ . At a power level of 1 watt, they generate very small spurious signals of less than a nanowatt, as a result of their high linearity. These linear, low-resistance switches can enable significant improvements in the design of mobile phones.

For example, they can be used in RF modules that need to address the increasing number of frequencies at which modern mobile phones have to be able to communicate (e.g., GSM, UMTS, WLAN, Bluetooth, GPS, TV on mobile). The conventional solution is to place separate electronic circuits for each of these frequency bands. However, this results in an almost linear increase of the size and cost of the RF module with the number of frequency bands. A much more desirable solution is to design a switchable circuit (with RF MEMS switches) that can be reconfigured to the frequency at which it needs to communicate.[6,7] This reuse of electronics for multiple frequency bands will lead to a reduction of the size and costs of the total circuit.

Another example of the application of RF MEMS switches is to create adaptive circuits. [8] The impedance of the mobile phone antenna can be strongly affected by the environment. If the user places his or her hand on the antenna, this can cause a significant reduction of the phone's RF efficiency and a corresponding increase in power dissipation. With adaptive circuits, the impedance change can be detected and compensated, thus increasing antenna sensitivity and power efficiency.

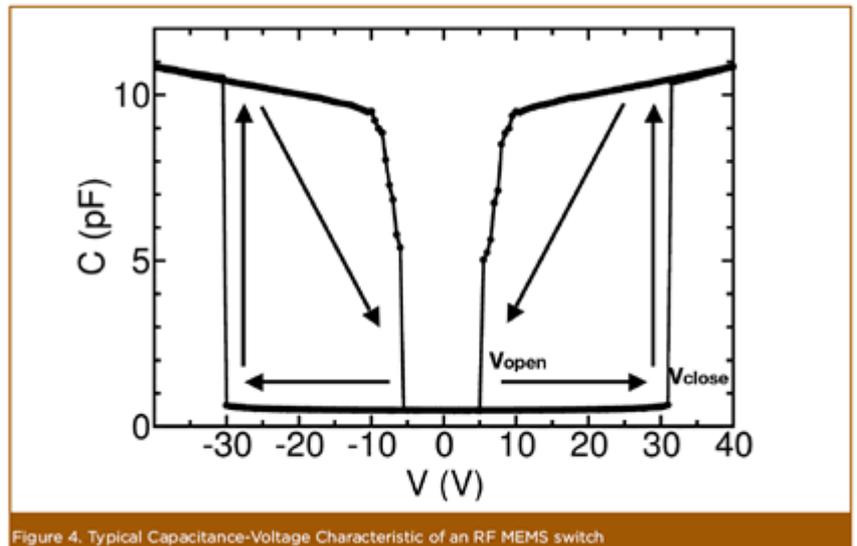
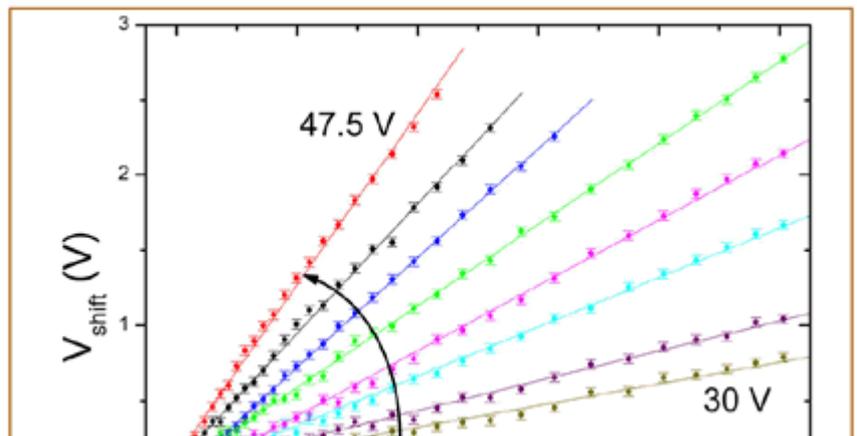


Figure 4. Typical Capacitance-Voltage Characteristic of an RF MEMS switch



# Conclusions

RF MEMS switches combine the low resistance and high linearity of mechanical switches with the miniaturization and low-cost production of semiconductor devices. The application of these switches requires a thorough understanding of a broad range of new physical phenomena at microscopic dimensions and their effect on the dynamics, manufacturability and lifetime of the switch. The application of RF MEMS switches in reconfigurable and adaptive RF products promises an increase in efficiency and sensitivity, and a reduction in size and cost of future mobile phones.

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