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IMPACT OF HUMIDITY OF AIR ON THE PROPERTIES OF CAPACITOR-VOLTAGE NATURE OF RF-MEMS CAPACITIVE SWITCH

SYED FOYSOL ISLAM[1], A.H.M. SAIFUL ISLAM[1], SHAMIM AL MAMUN [1], SAKEEB ADNAN SAGOR[1], AND A. A. M. MONZUR-UL-AKHIR[1]

[1]Faculty of Engineering, University of Development Alternative (UODA), Bangladesh.

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ABSTRACT

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The Capacitor-Voltage (C-V) features of RF-MEMS switches have already been studied. This research paper examined how the humidity influences the performance of the electronic devices as well as helps to find out how C-V characteristic curve shifted depending upon humidity and dried atmosphere. The experiment was conducted in the Communication Laboratory, Department of Electronics and Telecommunication Engineering, University of Development Alternative (UODA) in collaboration with the Department of Computer Science and Engineering, Faculty of Engineering, UODA, Bangladesh during the period January- May, 2009.

Keywords: Air Humidity, capacitive switch, electronic devices performance.

INTRODUCTION

Radio-frequency micro-electromechanical capacitive switches (RF-MEMS) are high performance devices with applications in telecommunication systems (Santos, *et al,* 2004). The capacitance-voltage (C-V) characteristic of these devices shows threshold voltages at both forward and reverse bias as the switch is turned ON and then OFF at the pull-in (VPI) and pull-out (VPO) voltages, respectively. The C-V curve changes during the switch operation and this has received much attention in the literature. Early work showed that the forward and reverse thresholds shift in the same direction (Reid, 2002; Yuan, *et al,* 2004; Kucko, *et al* 2006); this is referred to as the C-V shift effect. Recent work (Reid and Webster, 2002; Rottenberg, *et al,* 2004; Herfst, *et al,* 2007) showed another instability effect, namely, a C-V curve narrowing that occurs when the thresholds decrease in magnitude. Although both effects were attributed to dielectric charging, it is uncertain why different authors observe different effects. To explain these results various interpretations of the dielectric charging phenomenon in RF-MEMS were proposed. Moreover, published data usually relies on different test structures and measurement conditions which is a further cause of discrepancies. Even though it was shown that humidity may shorten the lifetime of the switch (Spengen, 2005), its influence on the C-V curve drift was not shown. For this reason we provide a simple experiment to show that humidity significantly affects the C-V performance of the switch.

In their most basic form, MEMS capacitive switches consists of a movable top electrode (bridge or membrane) suspended above a dielectric-coated CPW (coplanar waveguide) transmission line (Figure 1(a)). The design of the switch involves balancing of the electrostatic force (F_{el}) and the mechanical restoring force (F_k) used to close and open the switch, respectively. If the magnitude of the applied voltage (V) exceeds pull-in (V_{PI}), an electrostatic force (F_{el}) induced on the top electrode is greater than the mechanical force (F_k) and the electrode collapses onto the dielectric. Then, the capacitance of the device rises sharply. To open the switch and decrease the capacitance, the applied voltage must be reduced until the pull-out is reached (V_{PO}). In the high capacitance state (switch closed) the RF signal is coupled to the ground, while in the low capacitance state (switch open) the RF signal passes through the device. The capacitance and threshold voltages of the switch are defined by a common area between the top electrode and the signal line, air-gap height and the dielectric thickness and its permittivity. Since, the electrostatic force is proportional to the square of voltage ($F_{el} \propto V^2$) the ideal operation characteristic of the switch is symmetrical about 0V as shown in Figure 1(b). However, RF-MEMS reliability studies have shown that during switch operation the electrical properties of the dielectric change due to the dielectric charging phenomenon (Reid, J. R. 2002 ; Yuan, *et al,* 2004; Kucko, *et al,* 2006, Reid and Webster, 2002 ; Rottenberg, *et al,* 2004 ; Herfst, *et al,* 2007; Spengen, 2005).

The presence of parasitic charge (σ_P) in the dielectric appears as an additional voltage source (V_P) that distorts the electrostatic force in the air-gap of the device (F_{el}), which then is proportional to $(V - V_P)^2$. As a result, the threshold voltages (pull-in and pull-out) drift, this ultimately leads to device failure by stiction or screening. In the first case, the switch fails in the closed position; the membrane stays in the down state even if the applied voltage is reduced to zero. In the second case, the switch fails in the open position; the membrane remains in the up state after bias voltage application. The direction of the threshold voltage change depends on the sign of V_P that is determined by the net polarity of parasitic charge (σ_P) and how the bias voltage polarity is defined with respect to the switch electrodes.

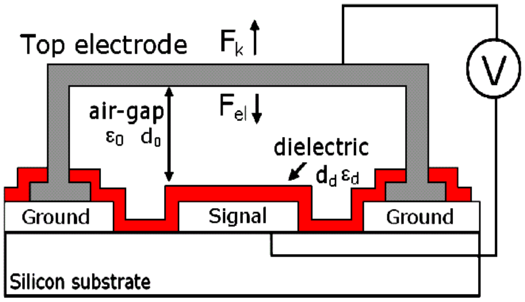

Figure 1. (a) Schematic of MEMS capacitive switch

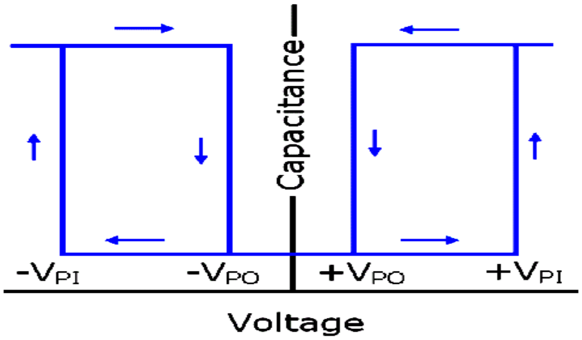

Figure1. (b) Ideal C-V operation characteristic for forward and reverse bias voltage

METHODOLOGY

In the experiment the C-V of the switch before and after dc bias stress applied was measured. However, in contrast to previous work which reports on measurements in either dry or humid ambient, we show results for both environments and at similar bias stress conditions. Therefore, we can directly observe the effect of humidity on C-V variation. The switch used in this work was built using a surface micromachining process and consists of a 100x100μm^2 membrane suspended by four springs above a CPW transmission line (Figure 2).

The CPW is coated with 130nm-thick PECVD (Chemical Vapor Deposition) SiO_2. The membrane and CPW material are aluminium and aluminium/1%-silicon, respectively. The air-gap in the open state is around 1.5µm. Due to process variation (i.e. variation of material residual stress and sacrificial layer thickness) the pull-in voltage varies across the wafer with a standard deviation of 1.2 V measured over ten random devices.

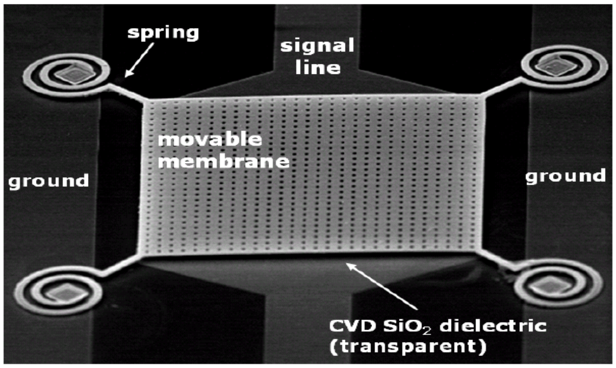

Figure 2. SEM image of typical RF-MEMS capacitive switch used in this work

RESULTS

The measurements were performed in room temperature by wafer probing on a Cascade Summit-1200 station with the wafer placed in the environment chamber. The system is equipped with an air-dryer that is capable of reducing the relative humidity of air to a dew point of -70oC (RH=0.01%). The mean humidity of the lab environment was 60% and when the air-dryer was turned off this level was measured inside the chamber. These conditions are later referred as dry-air and humid-air, respectively. The C-V measurements were performed with an Agilent-B1500A using a test signal of 100 kHz and 50 mV. A bias is applied between the membrane and the signal line and at the reverse bias the voltage at the membrane is negative and vice versa for the forward bias. The voltage sweep rate was 5 V/s with a step of 0.1V.

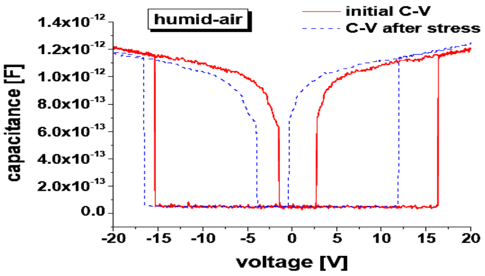

Figure 3. C-V curves of the switch before and after a bias stress (-20V) applied for 60 seconds and performed in humid-air environment

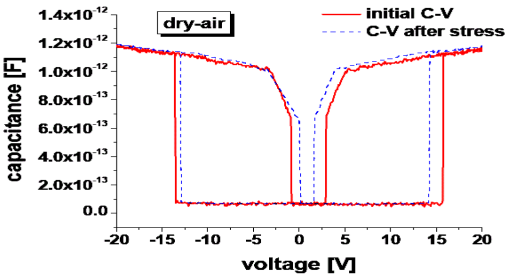

Figure 4. C-V curves of the switch before and after a bias stress (-20V) applied for 60 seconds and performed in dry-air environment

C-V characteristics of two similar switches measured in humid and dry environment are shown in Figure 3 and 4, respectively. Each figure includes two C-V measurements taken by a voltage sweep from -20V to +20V and back to -20V. After the initial C-V measurement the device was stressed with a bias of -20V for a period of 60 seconds, then the second C-V was taken.

Figure 3 and 4 show that the operating characteristic of the switch behaves differently after the same bias stress condition and measurement sweep but in different test environment. After the stress applied in humid-air the characteristic has "shifted" (four thresholds moved in the same direction), while after the stress in dry-air the characteristic has "narrowed" (four thresholds moved towards the center of the plot). Although the device behavior is different in both environments the failure mechanism due to stiction is common in each case. In Figure 3 the positive pull-out voltage ($+V_{PO}$) moves slightly to below 0V, whereas, in case of results from Figure 4 the negative pull-out ($-V_{PO}$) moves to above 0V.

From electrostatic theory, it is known that parasitic charge can shift the threshold voltage of the switch laterally, and that the direction of this shift depends on the net polarity of the charge and how the bias voltage polarity is defined with respect to the electrodes. In general, the electrostatic force required to pull-in or pullout the membrane decreases (absolute value of V_{PI} or V_{PO} decreases) when the dielectric charge is of opposite polarity to the polarity of the membrane and increases when these polarities are the same. This corresponds to a shift of the entire C-V curve laterally to the left and to the right by negative and positive fixed parasitic charge (not changing with time), respectively. This regularity has been experimentally confirmed in (Molinero, *et al,* 2006) for both polarities of charge which was fixed at the dielectric surface. Therefore, we can deduce that the shift of the C-V curve seen in Figure 3 is induced by the negative fixed parasitic charge (not changing within time of the C-V measurement) which was injected into the dielectric from the membrane during the stress time. Note that the polarity of parasitic charge is the same as the stress voltage (or charge on the membrane). Nevertheless, the narrowing effect seen in Figure 4, obtained in a dry-air environment but after the same bias stress condition, can not be explained in a similar way. A theoretical explanation of this effect was proposed by Rottenberg (Rottenberg, *et al,* 2004; Herfst, *et al,* 2007; Spengen, 2005 ; Molinero, *et al,* 2006 ; Rottenberg, *et al,* 2007) based on the assumption of non-uniformities of the dielectric charging and air-gap distribution. Another study presented experimentally that besides dielectric charging, mechanical degradation known as fatigue (Herfst, *et al,* 2008) and creep (Gils, *et al.,* 2007) can also cause the narrowing effect, depending on the type of applied stress. An investigation of the physics of the narrowing effect is currently being undertaken by the authors.

Figure 5 shows absolute value of the negative pull-in voltage during the lifetime test of 110 successive voltage sweeps from 0V to -25V. The environment humidity during this test varies as indicated in the figure. It can be observed that the pull-in change corresponds to the behavior observed in Figure 3 and 4 and depends on the environment condition.

CONCLUSION

In conclusion, we have shown that humidity significantly affects the C-V performance of an RFMEMS capacitive switch. It can be observed that after identical bias stress conditions the C-V curve "shifts" in humid environment while it "narrows" when the environment is dry. The results also demonstrate that although both effects raise similar reliability concerns due to device stiction, the root physical degradation mechanism can be different depending on test environment. Moreover, it is important to note that both polarity thresholds should be taken into account when physical interpretation of the C-V degradation mechanism is undertaken.

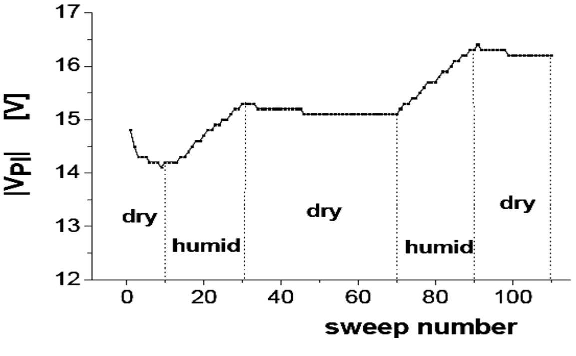

Figure 5. Absolute value of negative pull-in during the lifetime test of 110 successive voltage sweeps from 0 to -25V

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