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Comment on “Comparison of air breakdown and substrate injection as mechanisms to induce dielectric charging in microelectromechanical switches” [Appl. Phys. Lett. 92, 043502 (2008)]

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Comment on "Comparison of air breakdown and substrate injection as mechanisms to induce dielectric charging in microelectromechanical switches" [Appl. Phys. Lett. 92, 043502 (2008)]

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The purpose of this comment is to provide additional insight into the reliability of microelectromechanical capacitive switches (MEMSs) investigated by Molinero and Castañer [Appl. Phys. Lett. **92**, 043502 (2008)]. We show that the presence or absence of ambient humidity determines whether the shift in the capacitance-voltage (C-V) curve of oxide-based MEMS occurs as a result of voltage stress. In humid air, negative and positive shifts in the C-V curve are observed after negative and positive bias stress. In dry air no such shifts in the C-V curve are seen. These shifts are similar to those reported on oxide-based switches by Molinero and Castañer [Appl. Phys. Lett. **92**, 043502 (2008)] where they show shifts occurring in room ambient pressure, but not in vacuum. This indicates that not only air pressure but also air humidity can be responsible for shifts in MEMS. © *2009 American Institute of Physics*. [doi:10.1063/1.3255008]

The article by Molinero and Castañer[1] provides insight into dielectric charging phenomena responsible for the C-V instability in microelectromechanical capacitive switches (MEMSs). The author showed that at some ambient conditions the physical mechanism responsible for dielectric charging and C-V shifts can be enhanced. This is important as MEMSs are still in the research phase and the majority of authors in the literature report experimental data obtained from unpackaged devices where various environmental effects can exist. In the work by Molinero and Castañer, MEMSs with two different dielectrics were used, 70 nm thick thermally grown silicon oxide and 600 nm thick deposited silicon nitride. In both structures, the dielectrics were placed on the bottom electrode composed of highly doped silicon. The moving electrodes were suspended in air above the dielectric and were made of aluminum and polysilicon for oxide and nitride devices, respectively. Experiments conducted on oxide devices in ambient air (atmospheric pressure, room temperature, and humidity) showed negative and positive shifts of the C-V characteristic after applying negative and positive stress, respectively. The same experiment performed under vacuum did not cause any significant changes in the C-V. The authors postulated that the shifts were due to the physical process of air breakdown (ambient conditions) which charges the oxide surface, as in the absence of air (vacuum condition) there were no shifts observed. Molinero and Castañer[1] have also shown that the results from nitride devices did not depend on whether experiments were conducted in air or vacuum and the charging on such structures was explained by charge injection form the bottom electrode. Also, their work showed that the sign of the trapped charge was different for oxide and nitride structures. The difference between the results from both structures may be due to large difference in the electric fields used during the stress condition, e.g., 5.5 and 0.6 MV/cm for oxide and nitride based device, respectively.

It is well known that water vapor present in ambient conditions can bond to the surfaces.[2,3] The presence of this moisture can change the properties of the dielectric and affect its leakage current.[4] Unlike in standard complementary metal oxide semiconductor (MOS) devices, in MEMS the active surfaces, e.g., top surface of the dielectric and bottom surface of the moving electrode, are exposed to the test environment. Therefore during ambient experiments moisture can easily accumulate at both surfaces whereas at low pressure this effect is minimized as moisture is partially removed.[2]

In this work, we show that by changing the ambient humidity (at constant air pressure) the experimental results on our oxide-based switches are similar to those obtained on such switches by Molinero and Castañer. The MEMS used in this work are $100 \times 100\ \mu m^2$ aluminum membranes suspended 1.5 μm above an aluminum bottom electrode that is coated with 130 nm plasma-enhanced chemical-vapor deposited silicon oxide. A scanning electron microscopy (SEM) image of a typical device is shown in Fig. 1. Assuming that the structures used by Molinero and Castañer[1] do not suffer from MOS instability that is related to the trapping properties of semiconductor/dielectric interface,[5] we can infer that the MEMS used in our experiments are similar because no semiconductor/dielectric interface exist in our structures. In

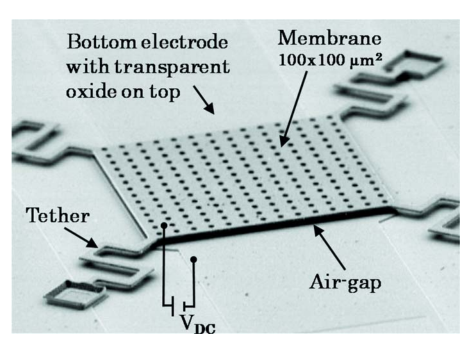

FIG. 1. (Color online) SEM image of $100 \times 100\ \mu m^2$ rf MEMSs capacitive switch.

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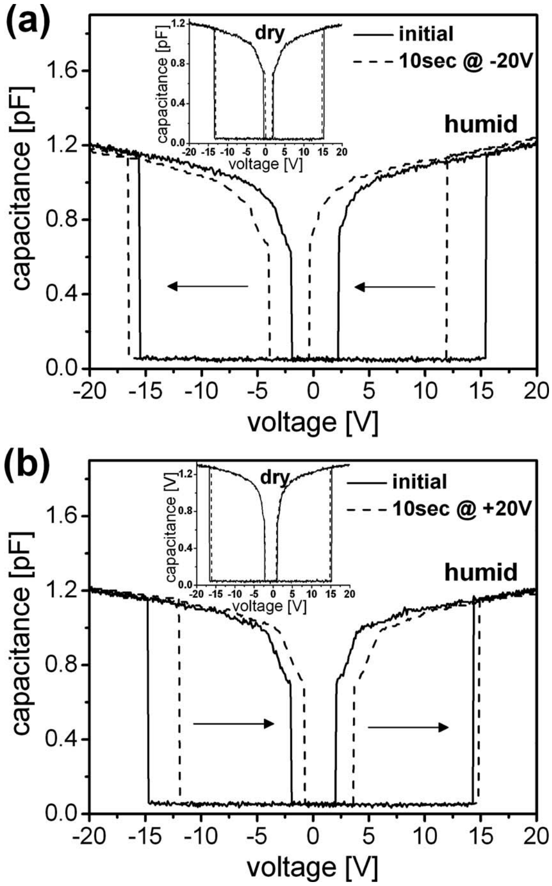

FIG. 2. C-V characteristics before and after dc bias stress applied for 10 s on 100×100 μm^2 rf MEMSs switches performed in humid-air and dry-air (shown in the insets) conditions, (a) negative stress of -20 V, and (b) positive stress of +20 V.

our work the stress field is 1.5 MV/cm and only oxide devices are investigated. The C-V measurements are performed using an Agilent B1500A (semiconductor device analyzer that provides integrated capacitance-voltage and current-voltage measurements) and wafer probing on a cascade summit station. The bias is applied to the membrane with respect to the electrode. The wafer was placed in the chamber with an air dryer that is capable of reducing the relative humidity (RH) of air from the lab-ambient (60%) to 2%. In this work, the C-V of the oxide switches measured in the humid air (60%) is compared with that from the dry air (2%). We also show the current-voltage (I-V) curves for both conditions.

The experimental data reported by Patton in Ref. 3 in Fig. 4 shows that at RH from 0 to around 50% negligible water absorption on the oxide surface can occur. Above 50% RH this absorption increases and a monolayer film ($\approx$4.56 Å) of water at around 60% can be expected. A similar condition on the surface of the membrane can be assumed. However this depends on a number of factors, e.g., material hydrophobicity, contamination, surface morphology, etc.

The experimental C-V data for the oxide switches are described in Figs. 2(a) and 2(b) for the negative and positive stress, respectively. The main plots of both figures describe the results obtained in humid air whereas insets show the data from dry air. Each of the four plots was obtained on a different device of the same type and on the same wafer. The measurement procedure of the plots shown in Fig. 2(a) was: first, the initial C-V sweep was performed from -20 to +20 V and back to -20 V. Second, negative stress at -20 V for 10 s was applied. Finally, another C-V sweep was performed from -20 to +20 V and back to -20 V. The measurement/stress procedure of the plots shown in Fig. 2(b) was similar; however the sweeps were performed from +20 V to -20 V and back to +20 V. Note that the measurement/stress procedure in humid and dry air for a given stress polarity is the same.

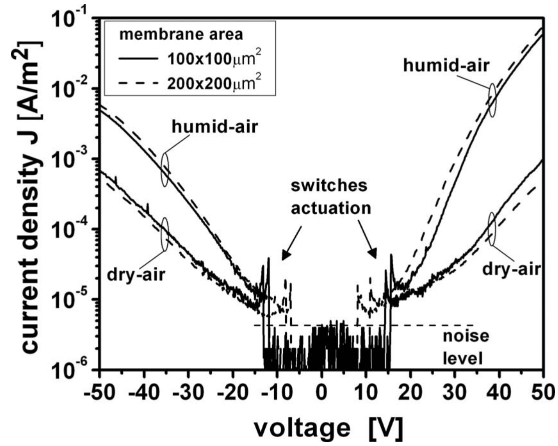

FIG. 3. J-V forward and reverse characteristics of rf MEMSs switches in humid-air and dry-air conditions for two device areas.

It is seen from the main plot of Fig. 2(a) that the negative stress on the switch in humid air causes a negative shift of the C-V; the forward and reverse thresholds shift toward the left along the voltage axis. The same test performed for the positive stress (+20 V) causes a positive shift in the C-V, as shown on the main plot of Fig. 2(b). These shifts are consistent with that observed on oxide switches by Molinero and Castañer. The same experiments were performed in dry air are shown in the inserts of Figs. 2(a) and 2(b). No shifts in the C-V curve occur. However, a small amount of narrowing is observed. The negative and positive shifts indicate that net negative and net positive sheets of charge[6] were induced in the dielectric after application of negative and positive stress, respectively. The C-V narrowing indicates that different physical origin dominates, e.g., mechanical degradation,[7] nonuniform charging,[8] or interfacial polarization.[9]

The data suggests that the physical mechanism responsible for dielectric charging and resulting in C-V shifts on the oxide MEMS can be enhanced not only by air pressure but also by air humidity. Figure 3 describes J-V (current density-voltage) characteristics measured on oxide switches with different device areas. The data shows that the measured oxide conduction is very sensitive to the humidity; current is significantly enhanced at 60% RH with respect to that measured at 2% RH. This may indicate that the moisture accumulated at top surface of the dielectric enhances the electrical conductivity between the membrane and the dielectric, thus enhancing the total current measured on the switch. At higher current and at the negative stress on the membrane more electrons are injected into the dielectric, causing more negative charge to be trapped at the surface than at the lower conduction. Similarly at the positive stress, higher injection of electrons into the membrane from the dielectric can occur, leaving behind positive charge at the surface. In MEMS the charge closest to the dielectric-air interface has the most significant effect on the electrostatic behavior.

The purpose of this comment is to provide additional insight into the reliability effects of MEMS capacitive switches. It was shown that the presence of humidity can determine whether the shift in C-V curve of oxide-based MEMS occurs as a result of voltage stress. In humid air, negative and positive shifts in the C-V curve are observed after negative and positive bias stress. This indicates that net negative and net positive charge in the dielectric is induced for negative and positive bias, respectively. In dry air no such shifts in the C-V curve are seen. Moreover, it is observed that current conduction measured on such structures significantly increases at higher RH. It is clear that humidity can play an important role in MEMS structures that are investigated in room-ambient conditions. However, it should be pointed out that the effect of humidity can vary for different dielectrics, or even the same dielectrics with different processing due to variability of material hydrophobicity, both for silicon oxide[10] and silicon nitride[11] dielectrics.

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