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Experimental isolation of degradation mechanisms in capacitive microelectromechanical switches

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DC and bipolar voltage stresses are used to isolate mechanical degradation of the movable electrode from charging mechanism in microelectromechanical capacitive switches. Switches with different metals as the movable electrode were investigated. In titanium switches, a shift in the pull-in voltages is observed after dc stressing whereas no shift occurs after the bipolar stressing, which is to be expected from charging theory. On switches with similar dielectric but made of aluminium, the narrowing effect occurs regardless if dc or bipolar stressing is used, which indicates the mechanical degradation as the mechanism responsible. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4726116]

The reliability problems of capacitive microelectromechanical (MEM) switches are hindering commercialization of such devices for a range of microwave applications.[1] The capacitance-voltage (C-V) curve of the switch changes over the device lifetime due to reliability problems and this received much attention in the literature.[2–10] While charging mechanism has been reported as the primary reliability problem of capacitive switches, the C-V curve instability can also occur due to mechanical degradation of the movable electrode. The device cross section and ideal C-V curve of a switch used in this work are shown in Fig. 1. The switch consists of the top movable electrode (membrane and springs) and the bottom electrode (coplanar waveguide, CPW) coated by a thin layer of dielectric. When the membrane is in the up-state, the radio frequency (RF) signal passes through the CPW. The application of the bias above the pull-in ($V > V_{PI}$) between the membrane and the signal line causes the membrane to collapse on the dielectric. This increases the capacitance of the device coupling the RF signal to ground. To release the membrane, the voltage has to be decreased to below the pull-out ($V < V_{PO}$).

The ideal C-V curve is symmetrical around zero bias due to electrostatic principle of switch actuation, i.e., the electrostatic force on the movable electrode is proportional to V^2. If parasitic charge in the device (e.g., in the dielectric on top of the central line) or around the device (e.g., in substrate or in the CPW gaps) due to bias stress exist and acts on the movable electrode, the whole C-V curve can shift on the voltage axis toward the positive or negative direction or narrow when the threshold voltages decreases in magnitude.[2–6] The narrowing effect has also been attributed to mechanical degradation of the movable electrode.[6–8] Currently, many capacitive switch technologies are presented in the literature where variations in threshold voltages are observed. However, it is not always clear if charging or mechanical degradation is the dominant reliability problem as this can depend on the switch technology, e.g., processing conditions, materials, and device layout. This work shows a method that isolates experimentally the two physical degradation mechanisms.

The pull-in voltage for positive and negative bias polarity in a capacitive MEM switch can be described by

$$V_{PI} = \sqrt{\frac{8\mathrm{k}}{27\varepsilon_0 \mathrm{A}}\left(\mathrm{g} + \frac{\mathrm{d}}{\varepsilon_\mathrm{d}}\right)^3} + f(\sigma). \qquad (1)$$

where k is the effective spring constant of the movable electrode, ε_0 and ε_d are the permittivities of the free space and the dielectric, A is the area of overlap between the membrane and the central line, g is the air-gap height, d is the dielectric thickness, and $f(\sigma)$ is the function describing the additional potential due to parasitic charge that appears in the device (or around the devices) due to bias stress over the device lifetime. Considering Eq. (1), it can be noted that the pull-in voltage can change from the initial value if (i) the change in the parasitic charge is non zero as a results of applied bias, i.e., $\Delta\sigma \neq 0$ and (ii) the effective spring constant of the device changes due to mechanical degradation of the movable electrode (membrane and springs) as a result of the mechanical forces during down-state, i.e., $\Delta k \neq 0$. In this consideration, we assume that A, d, ε_0, and ε_d cannot change over the test times in this work and the air-gap height g can change as a result of mechanical degradation as described in (ii). Taking into account the above conditions, it is proposed in this work that the bipolar and dc voltage stresses (Fig. 2) can be used to isolate the mechanical degradation from the charging phenomenon. In bipolar stressing, the magnitude of bias levels (+V and −V) is higher than the pull-in voltage of the switch. Also, the transition time between bias levels (from +V to −V and vice versa) is significantly shorter than the mechanical response time of the switch. In such conditions, the movable electrode cannot react mechanically to changes between bias levels and remains in the down-state over the entire stress time t_{bip}. At the same time, because the bias changes polarity at high frequency (in the range of kHz) and the duty cycle is set to 50%, the charging mechanisms would be significantly limited, i.e., the change in parasitic charge will be close to zero, $\Delta\sigma \approx 0$. In dc stressing, the stress time is set equal to the bipolar stress time, $t_{dc} = t_{bip}$. Thus, switches in both experiments undergo the same mechanical stress as the total down-state times are the same. However,

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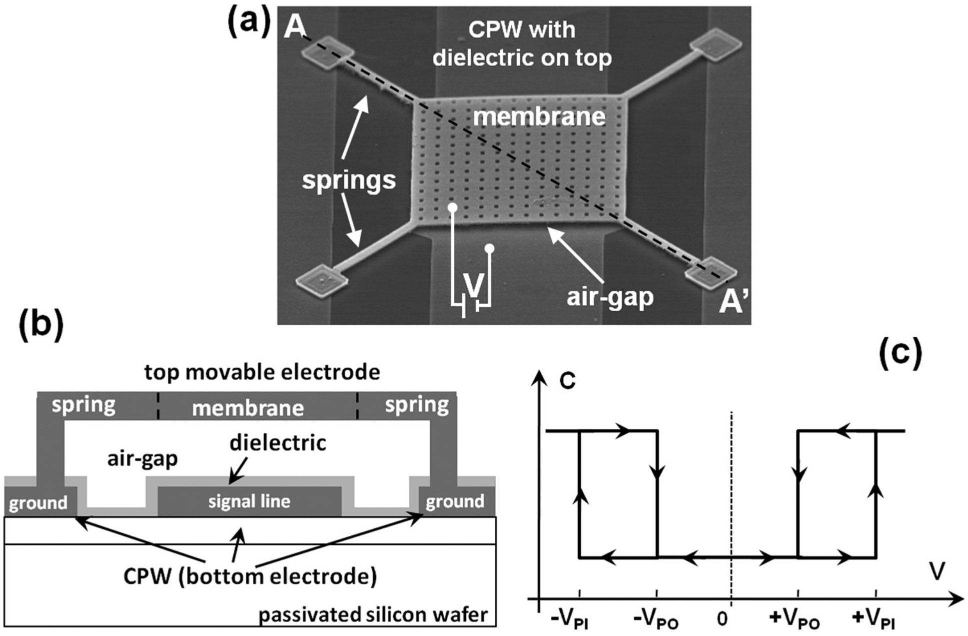

FIG. 1. (a) SEM image of a typical capacitive switch used in this work, the membrane area is $100 \times 100\,\mu\text{m}^2$, (b) cross section along AA′ cut-line, and (c) an ideal C-V characteristic of the switch.

during the dc stress the bias does not change polarity over the entire stress time and the charging mechanism should be significantly enhanced when compared with the bipolar stress conditions, i.e., $\Delta\sigma \neq 0$. From the theory described above, it can be concluded that in the switch under the bipolar stress the change in the pull-in due to charging phenomena should be significantly lower than that observed during the dc stress on the same device. Also, if the changes in pull-in voltages are seen to be comparable regardless of the bias stress type, then it would indicate that the mechanical degradation of the moving electrode is the dominant reliability problem. It must be noted that the charge injection and removal processes under positive and negative biases in bipolar stress are not identical.[9,10] Therefore, bipolar stressing will eventually result in charge build-up in the device. However, significant differences after relatively short stress times should be observed when compared with the dc stress.

To prove the theory above, we perform bipolar and dc stress experiments on two types of switches with layout as shown in Fig. 1. In both devices, the dielectric is 140 nm thick silicon oxide, substrate is low resistivity silicon passivated by $0.5\,\mu$m thick silicon oxide, and bottom electrode is $0.5\,\mu$m thick layer of aluminium with 1% silicon. The dielectrics have been deposited by plasma enhanced chemical vapor deposition. The switches differ in terms of the movable electrode composition, i.e., $0.5\,\mu$m thick titanium and $1.0\,\mu$m thick aluminum, thus were fabricated in two separate fabrication runs. Moreover, the processing conditions during the final release step (i.e., removal of the sacrificial layer in a plasma environment) were different for both switches: the titanium switches were released in a mixture of oxygen gas (O_2—90%) and tetrafluoromethane gas (CF_4—10%) at room temperature, whereas the aluminium switches were released in oxygen gas only at 220 °C.

The measurements of pull-ins are performed by C-V sweeps using an Agilent B1500A Device Analyzer and by wafer probing on Cascade station in a dry environment and at room temperature. A typical time for a single pull-in measurement is 2 s. The dc bias stress was supplied to the switches by Agilent B1500A whereas the bipolar stress by signal generator Agilent 33220A with a signal amplified by Falco WMA-300 to the desired bias levels. The transition times between bias levels in the bipolar signal were measured with oscilloscope to be $0.2\,\mu$s, significantly lower than the switching speed (mechanical response time) of switches used in this work, i.e., $\approx 100\,\mu$s. The bias in these experiments is applied to the membrane with respect the signal line. In experiments, three stress cycles have been performed; cycle 1: dc stress (0 Hz) for 10 min at -25 V, cycle 2: bipolar stress (1 kHz) for 10 min at ± 25 V, and cycle 3: bipolar stress (10 kHz) for 10 min at ± 25 V. During the experiments, the relaxation intervals at no bias were used before cycle 2 and cycle 3 to allow the pull-in voltages to return back to the initial values (± 0.1 V) after the stress in

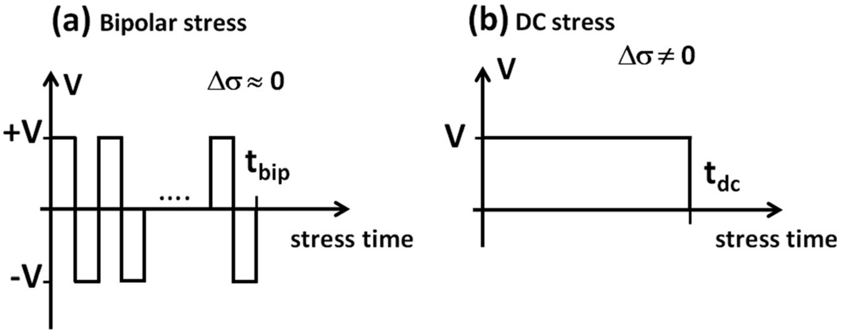

FIG. 2. The principle of (a) bipolar voltage stress and (b) dc voltage stress used in this work to isolate mechanical degradation from dielectric charging.

previous cycle. It was observed that the relaxation interval of 1 h was sufficiently long for pull-in voltages of aluminium switches to relax, while the relaxation of pull-in voltages of titanium switch required around 10 h.

The experimental data obtained on the titanium switch are shown in Fig. 3. Figure 3(a) shows the change in the magnitude of the negative and positive pull-in voltages after dc and bipolar stress cycles. Note that a negative change means that the pull-in has decreased in magnitude whereas a positive change means that the pull-in has increased in magnitude. According to the theoretical basis for the experiment, the observed change in the pull-in voltages under dc stress (i.e., the C-V curve shifts in a positive direction as shown in Fig. 3(b)) while exhibiting negligible pull-in voltage change under bipolar stress indicate that dielectric charging is the dominant reliability mechanism in titanium switches.

The same set of experiments performed on an aluminium switch yield different results (see Fig. 4). In the aluminium switch, both positive and negative pull-in voltages decrease in magnitude (i.e., the C-V curve narrows as shown in Fig. 4(b)). This narrowing effect is in contrast to the charging behaviour observed in titanium switches as it occurs regardless of whether a dc or bipolar stress is used. According to the theoretical basis for the experiments, these results suggest that the dominant reliability mechanism for aluminium switch is mechanical degradation of the aluminium metal. This analysis agrees with our recent study of aluminium based test structures published in Ref. 7. The difference between the positive and negative pull-in voltage change under dc stress, which disappears under bipolar stress, provides evidence that the shift effect (charging) is superimposed on the narrowing effect (mechanical degradation). While the substrate, bottom metal and dielectric material and the applied dc stress is similar for the titanium and aluminium switches, the experiments indicate significantly less charging in the aluminium devices compared with the titanium devices. This difference may be due to the difference in the processing conditions for both devices during the final release of the sacrificial layers.

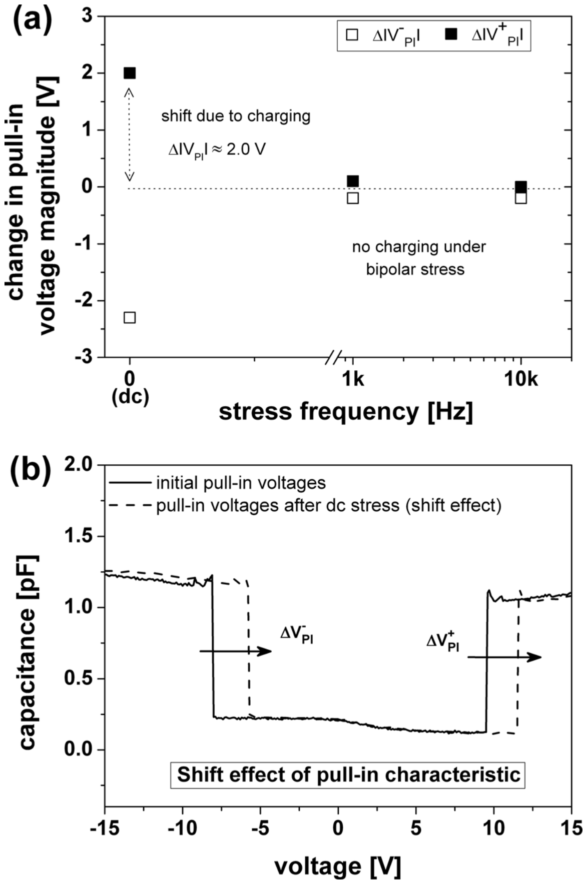

FIG. 3. (a) The change in the pull-in voltage magnitude after three stress cycles on the titanium switch. Note that a negative change in the magnitude of the pull-in voltage means that the pull-in has decreased in magnitude whereas a positive change in the magnitude of the pull-in voltage means that the pull-in has increased in magnitude. (b) The shift effect of the pull-in characteristic due to dc stress.

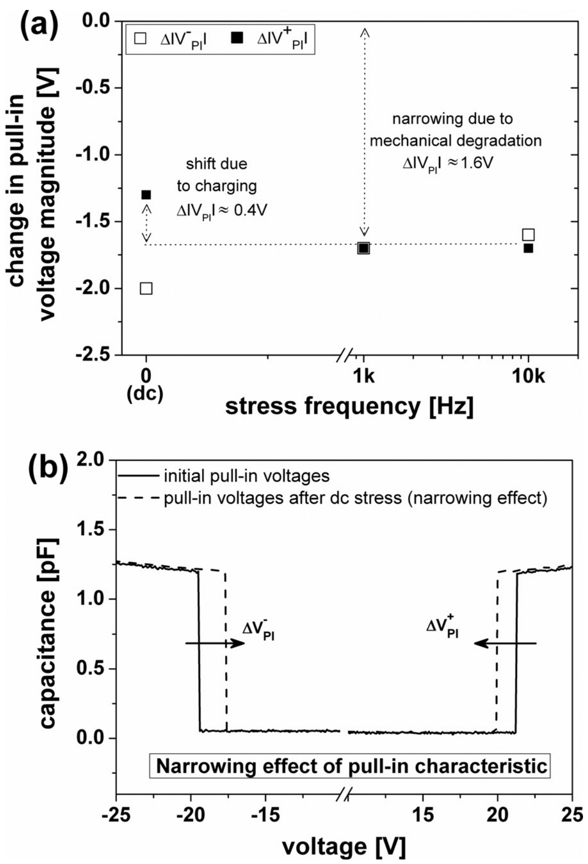

FIG. 4. (a) The change in pull-in voltage magnitude after three stress cycles on aluminium switch. Note that a negative change in pull-in voltage magnitude means that pull-in voltage has decreased in magnitude. (b) The narrowing effect of pull-in characteristic due to dc stress.

In the switches investigated in this work, the dominant degradation mechanism depends on the metal of the movable electrode. The results indicate that mechanical degradation dominates in aluminium switches and is responsible for the narrowing effect independently of the bias type. From the switch electrostatic theory, the pull-in is related with the spring constant of the switch by $|V_{PI}| \propto \sqrt{k}$ (see Eq. (1)), and the decrease in the spring constant can be responsible for the narrowing observer in aluminum switches. The physical mechanism that can potentially be responsible for this effect is the material relaxation mechanism, which results from viscoelastic phenomenon as described in Refs. 11 and 12.

The results indicate that this mechanical degradation does not occur in titanium switches and this can be attributed to higher melting point of titanium. In titanium switches, the charging is observed to be dominant, which is responsible for the positive shift effect under the dc stress; whereas under the bipolar stress, there is no shift as the net change in the dielectric charge is close to zero.

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