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A simple electrical test method to isolate viscoelasticity and creep in capacitive microelectromechanical switches

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A bipolar hold-down voltage was used to study mechanical degradation in radio-frequency microelectromechanical capacitive shunt switches. The bipolar signal was used to prevent the occurrence of dielectric charging and to isolate mechanical effects. The characteristics of material stress relaxation and recovery were monitored by recording the change of the pull-in voltage of a device. The creep effect in movable components was saturated by repeated actuation to the pulled-in position, while comparison with a theoretical model confirmed the presence of linear viscoelasticity in the devices. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4865584]

Radio-frequency microelectromechanical systems (RF MEMS) switches are an enabling technology for wireless communications, allowing tuning of high-frequency signals up to 120 GHz.[1] Their commercialization has been hampered by several reliability concerns which may cause these devices to fail under certain operating conditions. The dielectric layer of a capacitive switch is a key feature which allows the modulation of microwave signals. However, if this layer were to become sufficiently charged it could cause the device to remain closed even if the actuating bias were removed.[2,3]

Another cause for concern is mechanical degradation of the moving components, which can have a major impact on the switch properties.[4,5] Olszewski *et al.* demonstrated that a bipolar voltage applied to a switch may be used to differentiate between dominating electrical or mechanical degradation effects in a fully processed device.[6] In this paper, it will be shown that by extending this method to include monitoring the recovery characteristics of the device pull-in, further isolation and identification of individual mechanical degradation mechanisms may be achieved.

The mechanical effects present in a switch may be composed of permanent deformations (creep effect) and transient, fully recoverable (viscoelastic) mechanisms.[4,7] These effects have been studied in bulk materials by bending or tensile methods; however, these types of tests are unsuitable for the thin films used in MEMS manufacture. Mechanical tests on thin films have been performed using nanoindentation,[8] wafer curvature,[9] bulge testing,[5,7,10] and displacement-controlled tests[11] to extract the viscoelastic properties of materials. The disadvantages of these methods are (i) the damage caused by contacting a thin film means the experiment is not repeatable in the same location (ii) the information gathered about the material does not give feedback on how a real device will perform, and (iii) in many cases dedicated test structures are required for study. To overcome these difficulties some electrical test methods have been conceived to monitor viscoelasticity in MEMS devices.

Electrostatic actuation has been used by several groups to study viscoelasticity on air-based MEMS devices. The deflection of cantilever beams[12] and micropaddles[13] was monitored under an applied bias, and the change in voltage required to maintain the deflection over time was recorded. These tests had the advantage of non-contact with the device, but required the use of external feedback circuits and optical equipment. Scanning white light interferometry (SWLI) was used to monitor the deformation of a switch in the down-state over a period of time,[14] however, this dedicated test structure contained a dielectric and was actuated using a DC bias which causes charging. A purely electrical test has been performed on an air-based MEMS varactor by monitoring the S-parameters of the device.[15] The experiment measured the drift of the electrical resonant frequency over time, and charging was not an issue as no dielectric was used. In this work, an electrical test method will be presented which is suitable for quantifying the amount of creep and viscoelasticity in a fully processed dielectric-based capacitive MEMS switch. Unlike previous work, the switch will be mechanically strained using an electrical method which minimizes the effect of dielectric charging. The change in pull-in voltage will then be used as a measure of mechanical degradation.

The positive and negative pull-in voltage V_{PI} of a device may be determined by the following formula

$$\pm V_{PI} = \sqrt{\frac{8k}{27\varepsilon_0 A}\left(g + \frac{d}{\varepsilon_d}\right)^3}, \qquad (1)$$

where k is the effective spring constant, A is the area of overlap between the membrane and the bottom metal, g is the air-gap height, d is the thickness of the dielectric layer with permittivity ε_d, and ε_0 is the permittivity of free space. In the absence of dielectric charging during operation, changes in the spring constant and/or the air-gap of the switch result in a symmetric narrowing of the device C-V characteristic as the positive and negative pull-in voltage decrease in magnitude.

To monitor the switch mechanical degradation a stress relaxation and recovery experiment was implemented with a 50% duty cycle. First, a strain cycle was performed where the device was held in the down-state for a period of time. A subsequent recovery cycle was then performed for the same

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length of time where the switch remained in the open position under no bias. A key feature of this method is the bipolar hold-down voltage as described by Olszewski.[6] Many measurement techniques use a DC bias greater than the pull-in ($V_{DC} > V_{PI}$) to hold a switch in the down state. This can greatly contribute to charging of the dielectric.[16–19] Results from these experiments are difficult to interpret as they contain a superposition of mechanical and electrical degradation effects. In contrast to a unipolar DC hold-down voltage, a bipolar bias V_{BIP} alternates between a positive and negative polarity while maintaining a magnitude greater than the pull-in ($\pm V_{BIP} > \pm V_{PI}$). The transition time between voltage polarities of the bipolar signal is faster than the response time of the switch ($\approx 100\,\mu$s), thus ensuring the device remains in the down-state. In this way, a device is exposed to the same amount of mechanical stress as it is continuously held in the down-state; however the amount of charging is minimized by the alternating electric field. This technique ensures that the change in pull-in voltage can be used as an accurate measure of mechanical degradation. Full details of the bipolar test method can be found in Ref. 6.

The devices used in this experiment were fabricated on low resistivity silicon wafers, passivated by a 0.5 μm thick oxide layer, deposited by chemical vapour deposition. The device structure was defined using surface micromachining and featured a 0.5 μm thick bottom electrode composed of aluminium with 1% silicon. This was passivated with a 100 nm thick silicon oxide layer deposited by plasma-enhanced chemical vapour deposition. A polyimide sacrificial layer was spun and cured to a desired thickness and then a 1 μm thick Al membrane was cold sputtered on top. The polyimide was then removed by oxygen plasma leaving a free-standing metal membrane.

Two device types were fabricated and tested for their mechanical properties. The aluminium membrane in the first device (Type A) was sputtered using 2 kW RF power for 20 min, while the membrane of the second device (Type B) was sputtered at 1 kW RF power for 45 min. The bottom metal processing in device Type B was also performed at a lower temperature which resulted in lower surface roughness of the electrode. Note that as a result of different processing conditions device Type A and B have different effective spring constants k that were evaluated to be 3.5 N/m and 3.2 N/m, respectively. These k values were calculated from Eq. (1) using measured pull-in values and air-gap heights for each device.

The pull-in voltage of switch Type A is lower due to a smaller air gap while the downstate capacitance is also smaller due to higher roughness of the bottom electrode (Fig. 1). At the minimum stress voltage of ± 20 V the capacitance of the Type B switch is 1.3 pF, whereas for the Type A switch is approximately 0.5 pF. The capacitance of both devices increases with voltage in the down state; however, there is no significant difference in the capacitance slope for both devices, indicating a similar conforming effect of the membrane on the surface of the bottom electrode.

The devices to be tested were placed in a Cascade probe station in a dry environment at room temperature. C-V sweeps and DC voltages were applied to the switches using an Agilent B1500 parameter analyzer equipped with a capacitance measurement unit. Bipolar voltages were supplied using an Agilent 81110A pulse generator, where the signal was amplified to the required voltage using a high voltage amplifier. An Agilent 5250A mainframe was used to switch between actuation and measurement equipment.

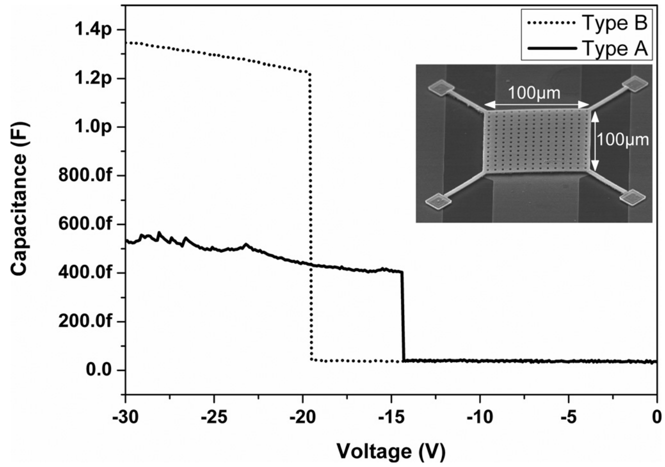

FIG. 1. A comparison of the negative pull-in voltage and C-V characteristics of the two device types. The measured air gap was 2.58 μm for Type A and 3.24 μm for Type B. Inset: SEM image of a typical $100 \times 100\ \mu m^2$ device.

To highlight the charging effect of a DC hold-down voltage, an experiment was performed whereby a switch was held in the down-state for 1 h with periodic C-V sweeps used to monitor the change in V_{PI}. Several DC and bipolar voltages were applied to close the switch and their influences were compared, as shown in Fig. 2.

It can clearly be seen that using a DC bias to close the device induced a larger change in the pull-in than using a bipolar bias. Almost no difference in ΔV_{PI} was observed between each of the bipolar biases; the overlapping curves in Fig 2(b) and approximately symmetric narrowing in Fig. 2(c) indicate purely mechanical degradation of the switch as predicted by equation (1). Resonance frequency and switch profile tests were also performed on devices before and after bipolar stressing. A change in both the resonant frequency and air-gap height was observed and hence a change in effective spring constant as a result of the hold-down experiments was confirmed. The voltage-dependent change due to DC biasing is proof of dielectric charging. This is further evidenced by the asymmetric narrowing observed after DC biasing, caused by a superposition of C-V curve shift due to charging and narrowing due to mechanical degradation. The bipolar method was therefore used for all subsequent experiments.

In previously published material, Hyun *et al.* reported on the effects of viscoelasticity in aluminium thin films.[5] A viscoelastic material is characterized by a material stress relaxation modulus given by a time-dependent ratio between material stress and applied strain $E(t) = \sigma(t)/\varepsilon(t)$. Using Hooke's Law, the effective spring constant of a material of cross-sectional area A and length L is given by $k = E\frac{A}{L}$, where E is the Young's modulus. For a viscoelastic material, the time-dependent modulus creates a time-dependent change in the effective spring constant. In the case of a movable electrode, this change can be monitored by measuring ΔV_{PI} over

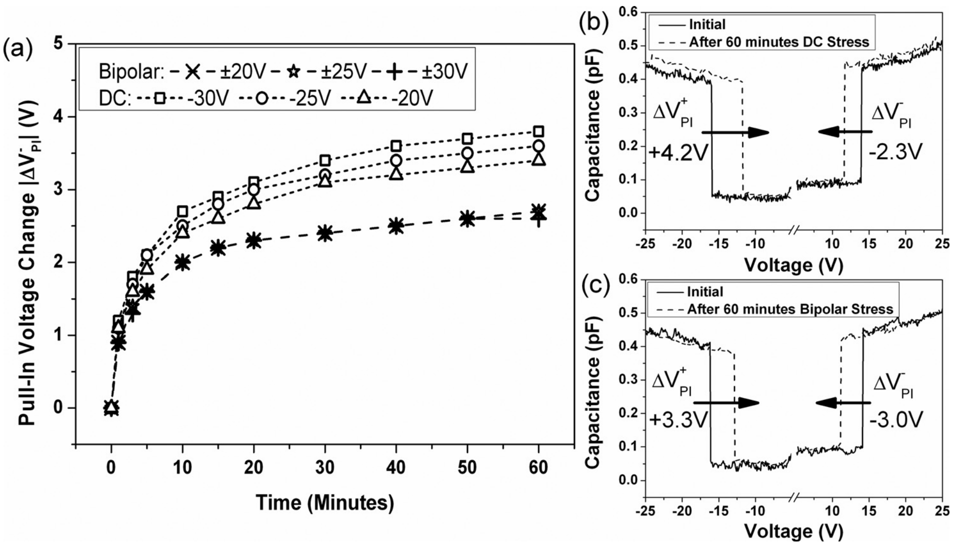

FIG. 2. (a) The change in the negative pull-in of a type A switch as it is held in the down-state using different DC and bipolar biases. (b) The asymmetric narrowing of the device C-V curve after DC biasing. (c) The approximately symmetric narrowing of the C-V curve after bipolar biasing. Similar results were obtained using positive polarity stresses.

time. The viscoelastic effect is a fully recoverable material stress relaxation mechanism perpetuated by grain boundary sliding.[11,20] A further classification—linear viscoelasticity, requires that this modulus be independent of the magnitude of stress and strain. This means the time-dependence of material stress relaxation during a strain cycle should be equal to its recovery during a recovery cycle. This phenomenon may be identified by monitoring the change in V_{PI} of a device using a strain/recovery test with a 50% duty cycle.

To study the viscoelastic effect in isolation, it is first necessary to saturate the pull-in change caused by the creep effect using repeated actuation and recovery cycles.[7] The creep effect is a viscoplastic deformation of the switch material that is highly dependent on the stress conditions to which a device is exposed.[10,21] In metals, creep is associated with the movement of material grains and is measured by a time-varying increase in strain in response to a constant stress. It is therefore important to saturate creep at the desired level of stress for the particular actuation scheme employed. Lower levels of stress will then experience no more permanent deformation. However, if the experimental conditions are changed more creep may occur in the switch which would cause a further change of the pull-in voltage.

In order to saturate the creep effect, both switches were subjected to repeated strain and recovery cycles. Both switches were actuated using a bipolar hold down voltage and held in the down-state for 1 h before being allowed to recover for another hour. The change in V_{PI} was measured using C-V sweeps during both the strain and recovery cycles. It was noted that a cumulative permanent change in V_{PI} appeared over time, but that this change tended towards saturation with repeated actuations. It was accepted that the creep effect was fully saturated when the final pull-in voltage no longer changed with subsequent test cycles. The creep saturation results are shown in Fig. 3.

After the devices had been creep saturated, the same strain and recovery technique was used to study any remaining mechanical degradation in the switches. Figure 4 shows the normalized strain and recovery characteristics obtained from these experiments. It was observed that the Kelvin-Voigt theory of viscoelastic[22] behaviour was capable of modelling the experimental data for both device types. This model takes the form

$$V_{PI}(t) = A \times \left(1 - \exp\left(-\left(\frac{t}{\tau}\right)^{\beta}\right)\right), \qquad (2)$$

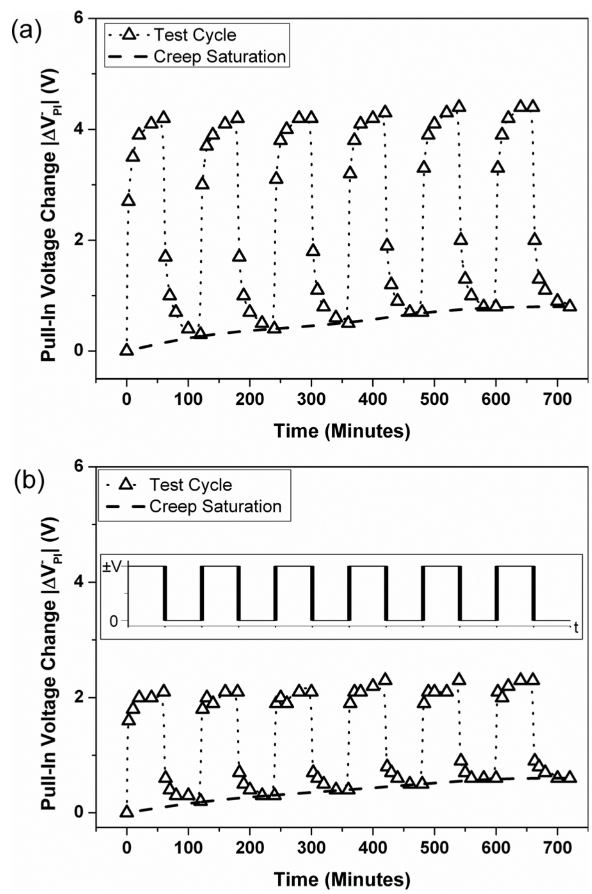

FIG. 3. Saturation of the creep effect in a type A switch (a) and a type B switch (b). The dotted line traces the magnitude of the change of pull-in during an individual strain/recovery cycle. The dashed line traces the accumulated permanent change of the pull-in over time. The inset of 3(b) shows a schematic of the strain and recovery cycles used to creep-saturate a device. Note that during strain cycles the switch is in the down-state at bipolar ($V = \pm 21$ V) bias and during recovery the switch is in the up-state at zero bias.

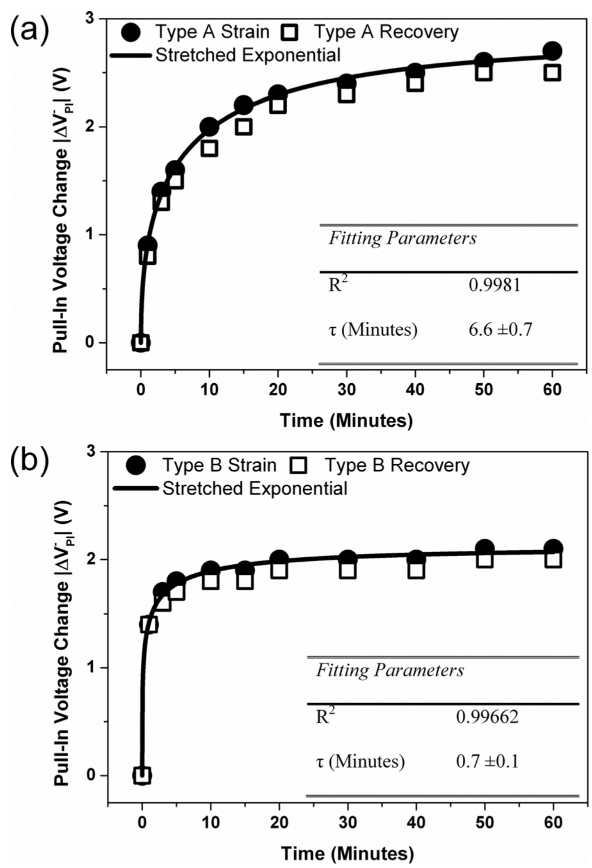

FIG. 4. (a) Normalized strain and recovery cycles obtained from device type A. Inset: fitting parameters obtained by the stretched exponential model applied to the strain curve. (b) Normalized strain and recovery cycle obtained from device type B. Inset: fitting parameters obtained by the same model.

where $V_{PI}(t)$ represents the change of pull-in over time, A is the change of pull-in at time $t = 0$, τ is the characteristic time constant of the material stress relaxation effect, and β is a stretching factor which accounts for the fact that a single exponential decay function is generally not sufficient to model experimentally derived curves.[4,7,10,11] The main fitting parameters are detailed in Figure 4.

Excellent agreement between measurement and viscoelastic theory was observed for both device types. The strain and recovery characteristics for each individual device show the same time dependence and hence identify linear viscoelasticity as the primary degradation mechanism in these switches. It is interesting to note that the recovery curve is offset from the strain curve by an average of 0.1 V (or approximately 5%) for both switches. This offset completely disappears after a few hours of recovery. The Type A device exhibited larger viscoelastic and creep effects and a longer time constant for viscoelasticity. We postulate that this difference in mechanical response is due to the different processing conditions of the top metals. The roughness of the bottom metal should have no influence on the magnitude or time constant of viscoelasticity. As can be seen in Figure 2(a), if the roughness was a factor then the viscoelastic magnitude should increase for larger stress biases and electrostatic forces. However, the response is identical for the range of bipolar voltages considered. Even though more dedicated thin film experiments are required to explain the difference in mechanical properties, the excellent agreement between measurement and viscoelastic theory for both device types which correlates with previous experiments by Hyun on thin film aluminium devices[5] demonstrates the accuracy of the new electrical method to study the mechanical reliability of capacitive microelectromechanical switches.

A method which utilizes a bipolar hold-down voltage to study mechanical effects in capacitive MEMS switches was introduced. This method can minimize the effect of dielectric charging which allows creep and viscoelastic effects to be isolated on thin film devices by monitoring the pull-in voltage change. Creep was isolated using repeated strain and recovery cycles while viscoelasticity was characterised by fitting strain and recovery experimental data to a theoretical model. The equal time dependence for strain and recovery curves identified linear viscoelasticity in our thin film aluminium devices, as previously observed by Hyun.[5] The experimental results are a strong validation of the bipolar hold-down method for straightforward electrical analysis of mechanical effects in thin-film capacitive switches. As new materials are constantly being investigated for potential use in RF MEMS,[10,20,23,24] the authors feel that this non-destructive method will prove very useful to device designers and process engineers.

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