HIGH RELIABILITY TOUCH-MODE ELECTROSTATIC ACTUATORS (TMEA)

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ABSTRACT

This paper discusses the failure modes frequently encountered in TMEA and reports on practical ways of increasing the time to failure. Humidity is identified as the main source of anomalies in the behavior of TMEA and charge trapping in the dielectric as the main cause of stiction. A method for direct charge measurement is derived and the measurements show good agreement with the calculated data. A new driving scheme is proposed that together with surface treatments desensitizes the actuator to environmental conditions. Actuators working without failure for over 40 millions cycles are reported.

INTRODUCTION

Electrostatic actuation is an efficient actuation method in terms of power consumption and structural complexity, being probably the only one that can be used to build large 3D arrays of actuators. In electrostatic actuators, the displacement is induced by the attractive force between a distribution of opposite sign charges placed on two electrodes. The electrodes are embedded in the constituent parts of the actuator (hereinafter called plates) of which at least one is movable. The charge is generated by a power supply connected to the electrodes. The actuators can be designed such as to allow or to prevent the direct contact of the plates.

In non-touch electrostatic actuators such as the comb drives[1], the plates are not coming in contact with each other during normal operation. These actuators are made out of conductive materials and can be regarded as single capacitors with spring loaded plates and a variable air gap. They can work reliably in a wide range of environmental conditions and for indefinitely long periods of time. However, the forces/pressures generated by such actuators are very small (fractions of an atmosphere), limiting their use.

In the touch-mode electrostatic actuators (TMEA), the two plates are allowed to come in touch. A thin (few thousands angstroms) insulating layer covers one or both electrodes to prevent current flow during the touch phase of the actuation cycle. In such actuators electrostatic pressures above ten atmospheres can be generated and held with relatively low voltages (<100V) and with very low power (μ W).

A particular type of TMEA is the rolling-contact actuator (Fig.1, [2]). In these actuators the plates are configured to create a variable gap: extremely narrow (close to zero) at one location (hinge) and very large (hundreds of microns) at another location (tip). Such actuators offer a unique solution to the conflicting relation displacement/driving voltage, allowing large forces and large displacements to be obtained with the same actuator.

The force/displacement benefits of TMEA are penalized by the practical problems associated with the ill-defined state of the dielectric surfaces and with the contacting surfaces. The literature records numerous reports of erratic behavior and failures of such actuators [3-5].

This paper will provide a brief overview of the failure modes frequently encountered in TMEA, will identify the causes behind

the failures and will offer practical solutions for high reliability touch-mode electrostatic actuators.

FAILURE MODES IN TMEA

Figure 1 shows the schematic structure of the rolling-contact TMEA used in our experiment. Listed below are the observed operational anomalies and failures:

Figure 1. Schematic structure of the rolling-contact TMEA used as test device .

- The DC voltage required to produce the actuation is significantly higher than the theoretical value;
- The generated electrostatic pressure in the closed state is much lower than predicted;
- The actuator closes and opens as expected at the first applied DC pulse; it does not close at the second pulse unless a higher voltage is applied; the voltage required to close increases with every cycle and eventually breakdown occurs;
- Under a stable DC voltage the actuator closes and then opens; in some cases it starts to vibrate between short closed and open states;
- The hysteresis associated with the non-linearity of the electrostatic force is reversed (the voltage to open is higher than the voltage to close) ;
- The actuator remains closed for many seconds after applying 0V; it opens immediately if the original DC voltage is slightly reduced;
- When kept closed under high electric field (>2MV/cm), permanent stiction occurs;
- After a certain number of actuation cycles (> 10^6 cycles), permanent stiction occurs;

It is obvious that the field responsible for the actuation is not related to the driving voltage through the simple formula $E=V/d$.

THEORETICAL CONSIDERATIONS

Most of the anomalies and failure modes observed in the rolling contact actuator are related to the closed state. In this state the actuator has the structure of a parallel plate capacitor. The force between the actuator plates can be written as:

$$F_{el} = \frac{Q^2}{2A\epsilon} = \frac{QE}{2} = \frac{\epsilon AE^2}{2} \quad ? \quad \frac{\epsilon AV^2}{2d^2} \quad (1)$$

(i) (ii) (iii) (iv)

where $|Q|$ is the total charge on each actuator plate, E is the field between the two plates, A the area of each plate, V is the voltage applied to the electrodes, ϵ_d is the dielectric constant of the dielectric covering the electrodes and d the total thickness of the dielectric layers (the dielectric layers on the two electrodes are supposed identical).

The formula connecting the force to the driving voltage (iv) is the most used but also the most misleading. It holds true only when between the electrodes there is a uniform dielectric. In the real structures, the surface of the dielectric represent a discontinuity that can affect the charge distribution, the field at the interface and the voltage to be used in (iv). The discontinuity can be in the resistivity of the surface layer, in its dielectric constant or can be associated with the surface roughness.

A solid dielectric is a complex material, being characterized by a large number of parameters. The most important ones are: the dielectric constant (ϵ_d); the dielectric strength (E_{max}); the bulk resistivity (ρ); the surface resistivity (ρ_s); the fixed charge (Q_f); the density and properties of interface traps (D_{it}); the density and properties of bulk traps (D_B); the chemical stability of the surface (water affinity); the mechanical properties of the surface (roughness). All these parameters have a strong dependence on the deposition method. Some of them (ρ_s , E_{max}) depend on the environmental conditions, while others (the charge injected and trapped in the bulk and surface traps) depend on the applied electric field, the number of actuation cycles, the geometry and the material properties of the electrodes.

During this study we tried to understand whether the observed anomalies are associated with a particular dielectric or are general to this type of actuators. Special attention was paid to the effect of the environmental conditions (mainly humidity) and the driving voltage on the reliability of the actuation process.

TEST STRUCTURES

In a previous study, the high frequency C-V characteristics of the thermal and PECVD silicon oxides and of the sputtered, LPCVD and PECVD silicon nitrides were compared using as test vehicles silicon-insulator-metal capacitors [7]. Except for the thermal oxide, the characteristics were indicative of significant amounts of fixed charge as well as charge injection and retention in the dielectrics. The measured dielectric strength for the thermal oxide and the LPCVD nitride was of about 5MV/cm while for the other dielectrics was of about 2.5 MV/cm. The dielectric constant of the oxides was close to 4 while for the nitrides it ranged between 7 in the LPCVD nitride to 12 in some types of sputtered nitride. In TMEA, the quantity $\epsilon_d E_{max}^2 / 2$ is very important as it gives the maximum electrostatic pressure that can be obtained with a certain dielectric. Materials with high dielectric constants and high dielectric strength are highly desirable.

Rolling-contact actuators with different configurations of the electrode/dielectric stack were fabricated and tested (Fig.1, Table 1). The fabricated flaps were 400 μ m long by 360 μ m wide and about 1 μ m thick. The devices were designed to have similar spring constants. Each actuator device consisted of an array of 5x5 flaps working in parallel.

Fabrication Process

In the structures type #1 and type #2, a thin dielectric layer was used to isolate the lower metal electrodes from the silicon wafer. In structure #1, 1000Å of sputtered nitride was deposited to form the lower dielectric; 500Å of Al was used as the sacrificial layer; 1000Å (type #1) and 2000Å (type#2) sputtered nitride were deposited as the upper dielectric, followed by a chromium upper electrode and about 0.9 μ of sputtered nitride as the flap body. The upward bending of the flaps was

controlled through the stress in the layers. Contacts were opened to both electrodes by dry etching. Cr/Au was deposited and patterned to define the contact pads. The lateral definition of the flaps was done by dry etching the nitrides down to the sacrificial layer. The sacrificial aluminum was etched in KOH and the flaps released. After the final rinse the wafers were dried by using the freeze—drying technique [6].

Structures #4 started with <100> silicon wafers followed by 500Å thermal oxide, blanket implant and anneal, 2000Å LPCVD nitride, deposition and patterning of 500Å Al sacrificial layer, deposition and patterning of 500Å Cr for the upper electrode, deposition of 1 μ m sputtered nitride, continued to completion as for structures #1 and #2.

Table 1

Structure Type	Lower Dielectric		Upper Dielectric		Electrodes	
	type	d ₁ [Å]	type	d ₂ [Å]	#1	#2
#1	Si ₃ N ₄ Sputtered	1000	Si ₃ N ₄ Sputtered	1000	Cr	Cr
#2	No Dielectric		Si ₃ N ₄ Sputtered	2000	Cr	Cr
#3	SiO ₂ Thermal	1000	SiO ₂ Thermal	1000	Si*	Cr
#4	Si ₃ N ₄ LPCVD	2000	No Dielectric		Si*	Cr

*Highly doped

For structure #3 polysilicon was used as a sacrificial layer and oxidized polysilicon was used as the upper dielectric.

EXPERIMENTAL RESULTS

The effects of the dielectric material, of the environmental humidity, the type of driving voltage (DC vs. AC), the type of hydrophobic coating and the magnitude of the electric field on the operation of the test structures were studied. A method for the measurement of the accumulated charge in TMEA was developed and measurements were performed. Long term cycling was performed on different type of devices.

Humidity Effect

Measurements were performed on all the fabricated structures at relative humidity ranging from zero (nitrogen dry box) to 95% and for DC and AC driving voltages.

DC Driving. When driving the actuators with DC voltages at humidity levels above 35%, the effects (a-e) were observed in *all types* of test structures. Humidity proved to be the most important cause of anomalies and failure, much more important than the charging characteristics of the dielectric. When environmental humidity is reduced below 30% or the samples are heated at around 90°C, the effects (a-e) are very much reduced or completely eliminated.

On the other side, when the devices are operated in dry air or nitrogen and driven with DC voltages, the effects (f-h) appear. It was observed that the time scale of the experiments (duration of the closed cycle) and the magnitude of the driving field were strongly related to the time to open and with the occurrence of stiction.

AC Driving. By using a square wave, AC driving voltage with a frequency of a few hundred Hertz, the actuator could be operated (controllably closed and opened) at higher humidity levels (up to 55%). However, the generated electrostatic pressure was significantly reduced by increasing the humidity. At higher humidity levels the actuator could not be maintained in the closed position.

When the AC driving is used in dry air or nitrogen, the effects (f-h) are significantly reduced. The actuator opens promptly when the actuation voltage is brought to zero and it can be kept closed for long periods of time without inducing stiction. It was concluded that AC driving is effective in fighting the RC effects but it cannot fully overcome humidity effects. For reliable operation, the hydration of the dielectric surface has to be eliminated.

The above observation helped us in developing a refined electro-mechanical model of the TMEA which, except for the permanent stiction, is able to explain all the other experimental observations [11].

The Hydrophobic Coatings

All the silicon based dielectrics (nitrides and oxides) have on the exposed surfaces a thin native oxide which is highly hydrophilic (work of adhesion 20mJ/m^2 [8,9]). Such surfaces become easily hydrated, with the density of water molecules attached to the surface being strongly dependent on the relative humidity in the environment. In humidity levels above 60%, multiple layers of water are formed on the surface. To completely avoid the formation of hydrated layers on the dielectric surface, hydrophobic self assembled monolayers (SAM) having as precursors the octa-decyl-trichloro-silane (OTS) [8] and the per-fluoro-decyl-trichloro-silane (PFTS) [9] were used.

The Coating Procedure. Following the final sacrificial etch, the wafers were freeze-dried, tested and evaluated at a wafer level and stored as needed prior to the SAM coating. The coating process started with a thorough cleaning and oxidation using piranha ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2$ 4:1) at 115° for 1 min. This step was found to be very critical to the quality of the wafer-level coating. The rest of the process was performed essentially as reported in [9]. At the end the wafer was pulled vertically from water and let dry in an oven at 100° . Generally the wafer level yield of the coating process was higher than 95%.

The Properties of the Self Assembled Monolayers. The water contact angle measured on the OTS and the PFTS coated samples are of about 112° and 115° respectively [9]. The evaluated work of adhesion is $23\mu\text{J/m}^2$ for the OTS and about 2 to $5\mu\text{J/m}^2$ for the PFTS [9]. The thickness of the resulted SAM is about 15Å for the PFTS and about 28Å for the OTS. The dielectric constant of the layer is supposed to be between 3 and 4, as in other similar organic compounds. The resistivity of the monolayers is important for their application in TMEA but very difficult to evaluate. The simulation of the devices showed that the time constants observed in the DC operation of the actuators are strongly related to the electrical characteristics of the surface layers. From the comparison of the simulated and measured data, an equivalent resistivity of about 10^{15}ohm-cm was estimated for the OTS coated surfaces and of about $2 \times 10^{14}\text{ohm-cm}$ for the PFTS coated surfaces.

The Effect of Coatings on the Actuation Process. Test devices were coated with OTS (devices type #1) and with PFTS (devices type #1 and #3) and tested in humidity levels ranging from zero to 95%. The OTS coating completely removed the humidity effects, both for DC and AC driving. Fig 3 shows the dependence of the generated electrostatic pressure on the relative humidity for an OTS coated sample and a non-coated sample, both driven with a square wave AC voltage with peak value of 25V and a frequency of 200Hz. In order to evaluate the generated electrostatic pressure, a back-pressure was applied through a hole etched in some of the test devices. The magnitude of the pressure required to open the actuator was used as a direct indication of the generated electrostatic pressure. The OTS coated sample operated properly in humidity levels up to 95% while the non-coated samples stopped generating any useful electrostatic force

at humidity levels higher than about 35%. The AC driven PFTS coated devices could work in up to 95% humidity; the DC drive could be used up to about 70% humidity, becoming unreliable afterwards.

Even though the OTS coatings possess a work of adhesion significantly lower than that of the silicon dioxide, the OTS coated devices driven both in the DC and the AC mode showed enhanced in-use stiction as compared to the non-coated devices. We considered that as an indication of the fact that capillarity is not the primary cause for in-use stiction in our actuators. We speculate that the permanent stiction in the OTS coated devices can be caused by enhanced surface charging associated with the higher resistivity of the layer and/or by surface interactions taking place between the hydrophobic layers. On the other side, in the PFTS coated devices driven in the AC mode the stiction was virtually eliminated. Such devices were used for long term testing.

Fig. 3 The dependence of the generated electrostatic pressure on the relative humidity for coated and non coated TMEA.

The Charge Measurement Method

Strong experimental evidence supports the idea that in the TMEA the nature of in-use stiction is mainly electrostatic. The charge producing stiction should be mainly accumulated at the interfaces between the dielectric and the coating layer (in interface traps) and/or on the outer surface of the actuator plates, in the areas where surface roughness prevents the intimate contact between the two surfaces. A rough estimation of the charge required to produce stiction is given by the formula:

$$Q = \frac{A_c}{A} V_{\min} \sqrt{\frac{\epsilon_c}{\epsilon_d}} C_{ac} + \frac{A_g}{A} V_{\min} \sqrt{\frac{1}{\epsilon_d}} C_{ac} \quad (2)$$

where A_c is the contacting area, A_g is the non-contacting area, ϵ_c is the dielectric constant of the coating (3 to 4), ϵ_d is the dielectric constant of the insulator (9), C_{ac} is the capacitance of the actuator in the closed state (0.8nF) and $V_{\min}$ is the minimum voltage required to hold the actuator in the closed position (5V). From the above equation, the charge required to produce stiction is about 1.4nC , with possible values between 1nC and 2nC for different values of the involved parameters.

To measure the accumulated charge, a Keithley 617 Programmable Electrometer was used in the setup presented in Fig. 4. The measurement method is based on the fact that (i) in the closed state the distance between charges is much smaller than the thickness of the dielectric (about 20 times smaller) allowing the field to close on the accumulated charges and (ii) the thickness of the dielectric is very small, ensuring the induction of an equal charge in the electrode, once the accumulated charges are separated [10].

In the first step (Fig. 4, a) both electrodes are grounded, the electrometer being connected in series with the lower electrode.

After the null condition is realized, the top plate of the actuator is removed (Fig. 4,b) by using tape. The charge remaining on the lower plate of the actuator induces an equal and opposite charge on the lower electrode. The electrometer connected in series with the electrode integrates the current and gives the total charge. The measurements were done in dry air.

Fig. 4 Experimental setup for the direct evaluation of the accumulated charge in TMEA by using an electrometer *E* and by mechanically separating the charges [10].

The measurements performed on different structures indicated a *positive charge* between 0.8 and 1.2 nC on the lower plate of the stuck actuators, in good agreement with the estimated values. Measurements were also performed on new devices that did not show stiction and no charge could be measured.

The Long Term Tests

Non-coated devices as well as OTS coated and PFTS coated devices were subjected to long term cycling tests, in nitrogen for non-coated devices and in clean room air with variable humidity (from 14% to about 65%) for coated devices. The frequency of the actuation was between 0.3 and 20Hz. Only AC driving voltages were used. Testing of non-packaged as well as of packaged (but not sealed) devices were performed. The results are given in Table 2.

Table 2

Structure type	Driving Voltage	Env.	Cycles
#1-not coated	+/-16V, triangular	N ₂	1x10 ⁸
#1-not coated	+/-25V, square wave	N ₂	10 ⁶
#1-OTS	+/-30V, square wave	clean air	2.5x10 ⁵
#1-PFTS	+/-30V, square wave	clean air	1.8x10 ⁶
#1-PFTS	+/-30V, square wave	clean air	4x10 ⁷ *

* 8 months test; packaged;

CONCLUSIONS

The relative effects of the dielectric material, the environment, the surface properties and the amplitude and shape of the driving voltage on the operation and life time of a TMEA were examined.

It was determined that charge injection and trapping in the dielectric have little impact on the short term behavior of TMEA when moderate electric fields are used (<2MV/cm). The anomalies in the short term behavior of the TMEA are considered to be produced by the altered electrical properties of the dielectric surface and by the surface roughness. The variations in resistivity and dielectric constant associated with the surface of the dielectric generate charge and voltage

redistribution in the stack. All these effects are reduced when AC driving is used.

Humidity, through the hydration of the dielectric surface was identified as the major source of anomalies in the DC and AC operation. For the first time the humidity was clearly associated with the failure to close and hold the actuator in the touch-mode rather than with stiction.

Hydrophobic self assembled monolayer coatings were used in order to control electrical effects in TMEA rather than to prevent stiction. It was found that some hydrophobic coatings can actually enhance the in-use stiction.

We believe that in our actuators the residual in-use stiction is related to permanently trapped charges. A method for charge measurement was devised and the results found in good agreement with the estimations. The exact mechanism of charge injection is not clear and will be further investigated.

By using dielectrics with hydrophobic surfaces and AC driving voltage reliable long term operation could be obtained.

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