Dielectric Material Impact on Capacitive RF MEMS Reliability

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Abstract - The influence of different types of dielectrics on the switching behaviour and reliability of capacitive RF MEMS switches fabricated by metal surface-micromachining is investigated. Sputtered AlN layers are compared to PECVD Si_3N_4 and Ta_2O_5 layers. It has been found that switches with sputtered AlN can be operated without failure in a wide range of driving conditions. Besides the dielectric charging problem another degradation has been observed independent of the dielectric material. The effect only occurs for operation in ambient air and is probably caused by an electrochemical reaction.

I. Introduction

MEMS based switches have emerged as a serious alternative to solid state GaAs or Si based devices in microwave applications. A lot of devices have been already presented but no mass product is on the market up to now. Packaging and reliability issues are the major limiting factors [1].

The packaging problem results from the fact that the structural layers are usually made from highly conductive metals (Au, Al) to meet low loss requirements. Since the released structures easily degrade at elevated temperatures standard wafer-level packaging requiring 300÷400°C is not possible. Up to now, conventional housing of single chips is the common way. However, this is expensive due to the problems concerning the separation of wafers with free standing MEMS into individual units and the handling of them.

The reliability of capacitive RF MEMS switches is mainly restricted by the charging of the dielectric material in the active area. Up to now, the standard dielectrics is PECVD Si_3N_4 (PE nitride). It has a dielectric constant of 6÷7 and could be easily deposited at low temperatures. The main drawback is the strong charging affinity. Nevertheless, switches with PE nitride have been tested for billions of cycles without failure. It has been shown, that the total time the membrane is in the down position is the critical parameter and not the number of cycles to failure [2].

To minimise the charging at first the voltage applied to hold the membrane in the down position should be as low as possible. A further improvement could be obtained with an alternating voltage. However, since injection and removal mechanisms are not equal the charging in PE nitride cannot be suppressed completely [3].

As an alternative, PECVD SiO_2 or LTO have been used as dielectrics in capacitive RF switches. The oxide shows less charging and better breakdown stability compared to PE nitride. However, the dielectric constant k is much lower (typ. 2÷4) which results in a small capacitance ratio and consequently in an insufficient performance at low GHz frequencies. From this point of view materials with a high k seem to be more attractive for RF MEMS. In [4] a capacitance ratio of 166 have been reached for a switch with sputtered BST (k =20). In the same paper for PECVD Al_2O_3 a ratio of 22 is reported (k =9÷10). The discrepancy to the theoretical value of 99 is explained by the roughness of the Al_2O_3 layer. Probably for the same reason in [5] a ratio of only 13 has been obtained for devices with anodically deposited Ta_2O_5 (k = 25÷30). In both papers no results about the reliability of the switches is given.

It is important that the dielectric layers can be produced with high quality in advanced semiconductor equipment. Ta_2O_5 is promising as dielectrics for capacitors in DRAMs while AlN is used for BAW resonators. During the last years sputtering processes have been developed by several suppliers of semiconductor equipment. In this paper AlN, Ta_2O_5 as well as PE nitride layers have been integrated in the capacitive RF-MEMS switch process at Fraunhofer ISIT [6]. The reliability of the devices is compared.

II. Device description

Fig. 1 presents a cross-sectional view of the surface-micromachined electrostatic switch and a photo of a finished device. The membrane consists of an evaporated Ni layer (about 1 µm thick), the spring-type anchoring of thick electroplated Ni (about 16 µm). This provides a high design flexibility allowing the implementation of special structures for a compensation of thermally induced and intrinsic stresses. A more detailed description of design aspects can be found in [6]. Signal line and ground area below the membrane are formed from an Ta/Pt/Au/Pt stack. Below the bridge the signal line is covered by one of the dielectric layers under investigation, AlN, Ta_2O_5 or PE nitride. In case of AlN, the sputter deposition process was performed at Unaxis, Liechtenstein. To avoid high control voltages on the signal line two separated actuation electrodes with an additional PE nitride isolation (dielectric 2) are embedded in the ground area. The two Ni bars on top of the membrane should ensure a good flatness in the active area of the switch. The lines outside the switching area and all other interconnections consist of 2 µm thick electroplated Au. Sputtered Ta_2O_5 layers were only integrated in a process run with a previous switch design without actuation electrodes.

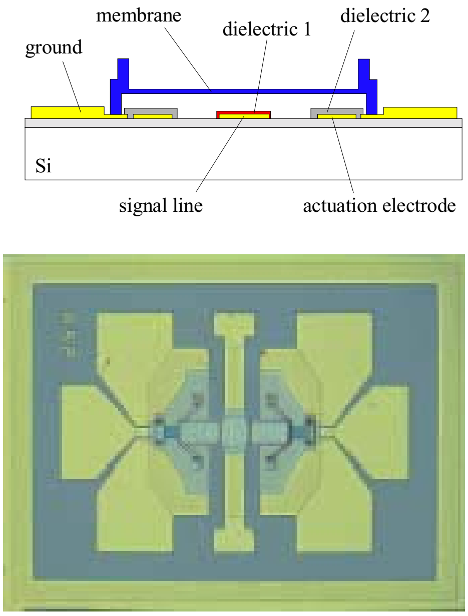

Fig. 1. Cross-sectional view of the switch and photo of a completely processed device. The membrane is 500 µm long and typically 100 µm wide.

III. Test set up

All tests were performed on wafer level on a manual probe station at laboratory conditions in ambient air or in a probe chamber at dry N_2 atmosphere. For capacitance measurements and the application of DC voltages below 40 V_{DC} a HP 4284A LCR meter was used. Voltage pulses above 60 V_{DC} were provided by a Keithley SMU 236. C_{off} and C_{on} as well as pull-in and breakdown voltages were obtained using the LCR meter only. The DC control voltage U_C applied to the signal line was ramped from 0 to 40 V in steps of 1 V. Simultaneously the capacitance values were measured.

All other experiments were performed using the actuation electrodes for switch operation powered by the SMU. The membrane was hold on ground to avoid an interference between LCR meter and SMU. After the DC control voltage U_C was applied to the signal line the membrane was pulled down by a short 60÷80 V_{DC} pulse on the actuation electrodes. Once in the down position the membrane should be held there by U_C for a predefined duration. For the tested switches a minimum value of 10 V_{DC} was required. After turning off the control voltage the membrane normally should move back to the initial up position. Cycling was executed usually at 1 Hz. To suppress the charging of the actuation electrodes the DC pulses were alternated in sign after each actuation. Three capacitance values were measured during a cycle. C_{off1} was recorded after turning on U_C while the membrane is still up. After switching down the membrane with the DC actuation pulse C_{on} was obtained. After U_C was removed C_{off2} was measured. At this moment the membrane normally should be back in the up position.

IV. Experimental results

Table 1 presents typical capacitance data for the different dielectrics obtained under laboratory conditions in air. C_{off} and C_{on} values correspond to 0 and 40 V_{DC} respectively if no earlier breakdown occur. As can be seen Ta_2O_5 gives the highest capacitance ratio but exhibit the worst breakdown behaviour. Most of the Ta_2O_5 devices fail during the first measurement. If not, they fail within a few seconds when 25 V_{DC} is applied permanently. Even for the much thinner PE nitride a significant higher stability was observed. The problem is the high k of Ta_2O_5 causing a 2 times higher field strength compared to PE nitride with the half thickness. But exactly high electric fields have to be avoided to prevent the injection of charges in a dielectric. Therefore, a high k not automatically is an advantage if the dielectric should be very thin. By increasing the air gap the capacitance ratio for PE nitride and AlN can be raised easily. Although, a value above 100 seems to be possible only with Ta_2O_5.

Parameter	Si_3N_4	AlN	Ta_2O_5
layer thickness (nm)	100	200	200
air gap (µm)	2,5	2,4	2,6
dielectric constant k	≈ 7	9,8	31
C_{off} (fF)	75	79	67
C_{on} (pF)	2,32	1,68	5,45
capacitance ratio	31	21	81
breakdown voltage (V)	≈ 35	> 40	≈ 30

TABLE 1

Typical capacitance data for switches with different dielectrics with an active area of 100 × 100 µm^2.

Charging behaviour

Fig. 2 illustrates the difference in the charging behaviour in air for identical switches with PE nitride and AlN. In both cases the membrane was switched down alternating by a ± 65 V_{DC} pulse on the actuation electrodes and hold with +20 V_{DC} on the signal line for about 90 s. For the device with PE nitride the capacitance decreases quickly after an initial peak and the membrane releases spontaneously within a few seconds although U_C is still present. Moreover, the membrane could be pulled down again without any actuation pulse only by changing U_C in sign. For the switch with AlN the membrane remains down until U_C is turned off. The capacitance has a very constant value. The switch can be operated repeatedly for various on-times under exactly the same switching conditions. The variation of C_{on} at the same U_C value with opposite sign is below 2 %.

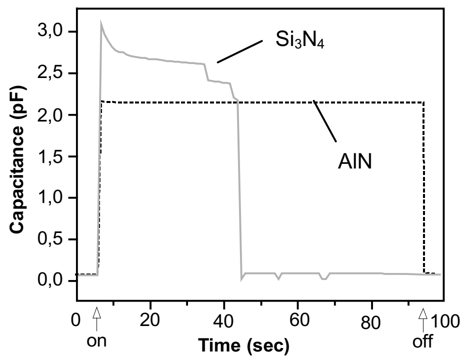

Fig. 2. Typical behaviour of the switch capacitance for identical devices with AlN and PE nitride operated with a positive DC control voltage.

The behaviour always remains the same for both materials. Even at 10 V_{DC} the membrane of a switch with PE nitride spontaneously releases after about 1 min. This has never been observed for devices with AlN. At 40 V_{DC} the membrane remains down until the control voltage is turned off.

But also for AlN layers charging effects have been measured. During the test illustrated by Fig. 3 U_C was increased from +15 to +30 V_{DC} in 1 V steps while the switch was cycled with 1 Hz in air. At about 22 V C_{off2} starts to oscillate. In cycles with positive actuation pulse the membrane sticks temporary after U_C is turned off and releases when U_C is applied again. At 25 V the temporary sticking occur during every cycle, independent of voltage polarity. Although this is a charge induced effect it should not be related only to the AlN in the active area of the switch since all the time C_{off1} remains low. Partially the temporary sticking may result from the charging of the PE nitride on top of the actuation electrodes. At 29 V C_{off1} increases as well due to a permanent sticking of the membrane.

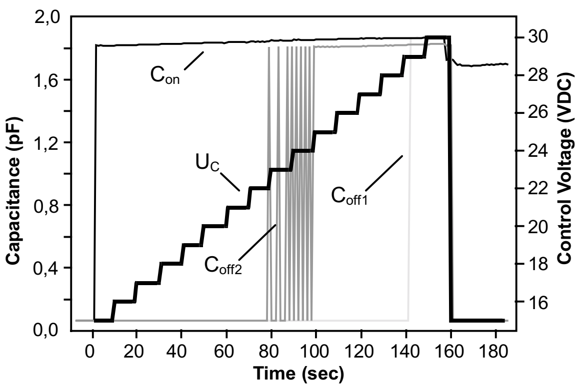

Fig. 3. C_{on} and C_{off} values for a switch with AlN cycled with 1 Hz at different positive U_C values.

Note, that the tested device correctly switches again after U_C is reduced to 15 V. This happens reproducible for switches with AlN but never could be achieved for devices with PE nitride.

The smaller charging effects in AlN probably result from a much higher structural quality. PE nitride usually has a weakly packaged amorphous structure with a high hydrogen content. The trap density is typically very high which is known to be the main reason for charging [3]. In contrast, the sputtered AlN layers are characterised by densely packed columnar grains with an excellent orientation. The AlN layers are much smoother than the PE nitride layers. It is assumed, that the defect density in such AlN is pretty low. Together with the large energy gap of 6,2 eV this could explain the reduced charging affinity.

Unfortunately, detailed charging experiments and cycling tests could not be performed for Ta_2O_5 due to the lack of switches with actuation electrodes. However, the impression is that the charging effect in Ta_2O_5 is as strong as in PE nitride.

Lifetime tests

Although switches with PE nitride could not be held down permanently by DC control voltages, cycling at 1 Hz was possible. In general, the lifetime is higher for lower U_C, for alternating U_C polarity and for higher cycling frequencies. In most cases the switches stick after some $10^3 \div 10^4$ cycles with positive or negative U_C of $10 \div 20$ V_{DC}, as shown in Fig. 4. But for single devices at 10 V_{DC} with alternating polarity, 10^6 cycles have been reached without failure. Obviously, at some special conditions during cycling a kind of equilibrium is established between charging and discharging processes in the PE nitride.

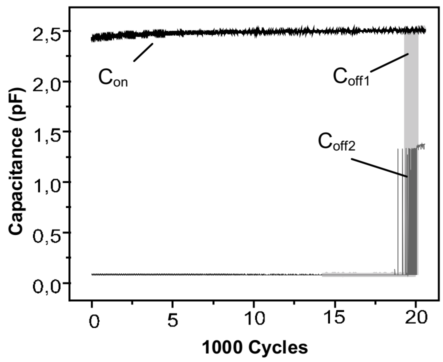

Fig. 4. Typical behaviour of a switch with PE nitride cycled at 1 Hz with +12 V_{DC}. After 17.000 cycles sticking occurs increasingly.

Fig. 5 presents a similar test for a switch with AlN cycled at 1 Hz using +12 V_{DC}. Instead of C_{on} and C_{off} the capacitance difference ΔC is plotted as a function of the number of cycles. The initial increase of ΔC within the first 1000 cycles was observed for all devices independently from the dielectrics. Probably, the effect can be explained by a rising smoothness of the contact surfaces repeatedly pressed together with high force. Nevertheless, for the device in Fig. 5 a mean value of 1,546 pF with a standard deviation of 0,009 pF could be calculated for the whole data set. The total down time of over 10^5 seconds is a factor 100 higher than the maximum values for PE nitride reported in [2]. The switch was still working without failure when the reliability test was stopped after 600.000 cycles.

But, at higher positive U_C values a strong decrease of ΔC occurs already after a few thousand cycles (Fig. 6).

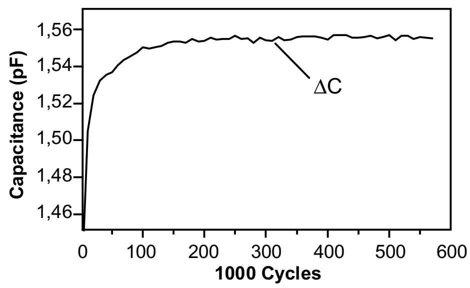

Fig. 5. Typical behaviour of a switch with AlN cycled at 1 Hz (200 ms downtime) with a control voltage of +12 V_{DC}.

Note, there is no contradiction to Fig. 3 where stiction occurs even at 22 V. That particular device was designed to have a lower membrane stiffness and consequently a lower restoring force. Other switches with a stiffer membrane could be operated easily at up to 40 V_{DC} without sticking. For switches with PE nitride the same effect has been observed if the device survived a sufficiently large number of cycles without sticking.

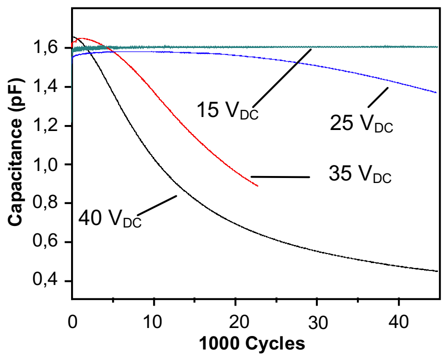

Fig. 6. Behaviour of ΔC for switches with AlN cycled with 1 Hz at different positive U_C values in ambient air.

This degradation can not be explained by charging. All stressed switches were still working without sticking. The effect is suppressed if U_C has a negative polarity. A possible reason for the problem could be the combination of noble metals with Ni. In the presence of a moisture film connecting the metals in the down state of the switch an electrochemical reaction can occur at the contact surfaces if a sufficiently high voltage with the "right" polarity is applied.

This assumption is confirmed by the fact, that ΔC remains stable also for positive U_C if the switch is operated in dry N_2. Fig. 7 compares two similar devices from the same wafer cycled with 1 Hz and an U_C of +30 V_{DC} at identical conditions in air and in dry nitrogen. Although the graph shows only the first cycles the device in N_2 has been tested for about 150000 cycles without degradation.

Additional tests with different frequencies and down times per cycle show that the degradation in air depends on the total down time of the membrane but not on the number of cycles.

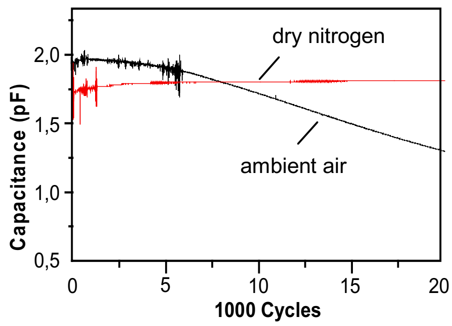

Fig. 7. ΔC versus the number of cycles for two similar switches with AlN tested under identical conditions in air and in dry N_2.

V. CONCLUSIONS

PE nitride and sputtered AlN have been tested as dielectrics for capacitive RF MEMS switches. Although some devices with PE nitride at particular conditions were operated for 10^6 cycles without failure they could not be held reliable in the on-state due to the charging of the dielectric. In contrast, switches with sputtered AlN can be operated repeatedly for any required duration in a wide range of conditions without charge induced failures. A total down time of over 10^5 seconds could be achieved. This indicates that sputtered AlN probably would allow to overcome the known reliability problems of capacitive RF MEMS switches.

A special degradation effect observed for both types of switches at higher control voltages in air is explained by electrochemical reactions in the presence of moisture. The degradation disappear if the devices are operated in dry nitrogen.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

[1] J. DeNatale, R. Mihailovich, "RF MEMS reliability", Proc. IEEE Transducers 2003, Boston, pp. 943
[2] I. deWolf, "Reliability investigation of RF MEMS", Proc. MEMSWAVE 2003, Toulouse
[3] G. M. Rebeiz (ed.), "RF MEMS Theory, Design and Technology" , John Wiley & Sons, 2003
[4] E. Berland et. al., "Dielectric Materials in MEMS switches: a comparison between BST and Al_2O_3", Proc. MEMSWAVE 2003, Toulouse
[5] X. Rottenberg et al., "Neuartige kapazitive HF-MEMS-Schalter", Electronic Embedded Systeme 04/03
[6] T. Lisec et. al., "Surface-micromachined capacitive RF switches with high thermal stability and low drift using Ni as structural material", Proc. MEMSWAVE 2004, Uppsala