ATOMIC LAYER DEPOSITION (ALD) TECHNOLOGY FOR RELIABLE RF MEMS

N. Hoivik, J. W. Elam[1], S. M. George[1,2], K.C. Gupta, V. M. Bright and Y.C. Lee

NSF Center for Advanced Manufacturing and Packaging of Microwave, Optical and Digital Electronics, Department of Mechanical Engineering,

[1] Department of Chemistry and Biochemistry
[2] Department of Chemical Engineering

University of Colorado at Boulder, CO 80309, USA

***Abstract* — A nano-layer inorganic coating technology has been developed to protect RF MEMS from electrical shorting as well as long-term reliability failures due to charging or moisture. The combination of alumina dielectric and zinc-oxide conducting layers can be constructed one atomic layer at a time. At 177 °C, the released RF MEMS devices can be coated on a wafer or as a single device with conformal, inorganic coverage where the thickness and electrical conductivity can be controlled to meet desired values. With additional chemical treatment, the surface could be made hydrophobic to avoid moisture-induced stiction. The long-term reliability problem is the main barrier that impedes the growth of RF MEMS applications. This novel atomic layer deposition (ALD) technology can help in overcoming this limitation.**

I. INTRODUCTION

In recent years there have been tens of demonstrations of different RF MEMS devices and their applications [1,2]. These MEMS-based RF circuits have achieved excellent tunability and reconfigurability with superior RF performance. At the present time, it is very clear that RF MEMS devices are enabling components for advanced RF microsystems. Unfortunately, it is also well known that these RF MEMS devices are not reliable for applications that demand trillions of cyclic movements or switches. Conducting particles might cause electrical short for surfaces not in contact and contact surfaces may get "stuck" onto each other after millions or billions of surface impacts. The study on the MEMS reliability affected by charging is a good example of these potential failures [3].

Most applications using MEMS-based accelerometers and digital micro-mirrors have proven MEMS devices to be reliable; in terms that they have demonstrated that intrinsic mechanical strengths of MEMS structures are very strong. Their endurance limits are beyond trillions of cyclic motions. Therefore, the major reliability failures of MEMS are surface related. For RF MEMS devices, there are two potential surface failures.

Figure 1 illustrates a potential electrical short caused by the electrodes themselves or by conducting particles for a MEMS-based variable capacitor [1]. In order to achieve very high capacitance variation, the gap between the electrodes has to be very small. After long-term operation, the gap could vary due to wear or an altered electrical field distribution. By accident, two electrodes might make a contact for a short. Or, some conducting particles might get into the gap and short the two electrodes.

Another well-known failure is associated with charging of the electrode surfaces. Figure 2 illustrates a cantilever MEMS switch pulled down by an electrostatic force. After cycles of up-and-down operations, the beam might get stuck to the electrode due to the charges accumulated on the electrode [3]. The charging effect is strongly dependent on the voltage applied. By increasing the voltage from 50 to 65 Volt, Goldsmith et al demonstrated the reduction of life cycles from 10 billions to only 10,000!

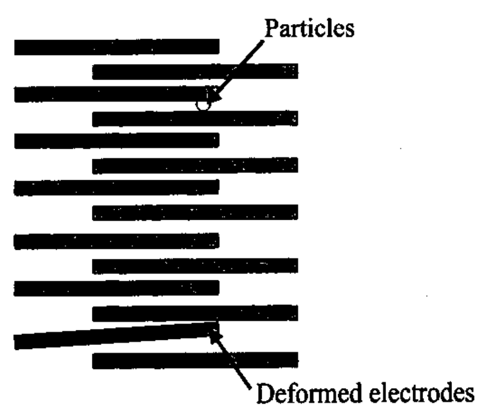

Fig. 1. Potential electrical shorts caused by deformed electrodes or conducting particles

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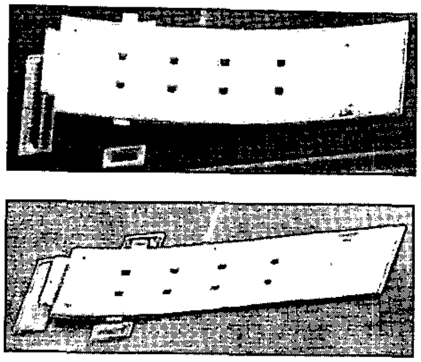


Fig. 2. Illustration of a potential MEMS reliability problem where the device permanently stuck to the substrate. [Courtesy of D. Miller, University of Colorado]

In addition to charging, moisture might induce another stiction failure due to the surface tension effects. Such adhesion failures might not be critical in a hermetic package, but it is the showstopper to the development of non-hermetic packages for cost-effective applications.

To avoid electrical shorting, we need conformal dielectric coating covering the entire conducting surface Figure 3 illustrates conformal coating of a cantilever beam structure. To control the charging effect, we need to make the dielectric layer electrically conductive to a certain level that would dissipate the charges accumulated with significant RF losses. To avoid moisture-induced stiction problem, we need a hydrophobic surface. All these features can be accomplished by a novel technology: atomic layer deposition (ALD) with a nano-scaled, inorganic, electrically conductive or non-conductive layer. With the inorganic coating, the protective layer might survive after billions or trillions of surface impact or rubbing. This paper will report the development of the coating process and the corresponding effects on the RF performance of a MEMS-based variable capacitor.

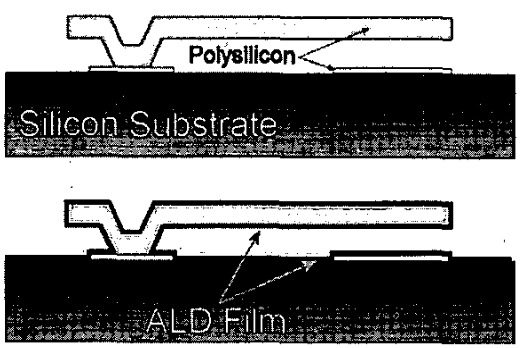


Fig. 3. Illustration of released cantilever beam and ALD film growth [4].

II. Deposition Process

A. Description of ALD deposition

Atomic layer deposition (ALD) is a thin film growth technique allowing atomic-scale thickness control. ALD utilizes a binary reaction sequence of self-limiting chemical reactions between gas phase precursor molecules and a solid surface [5]. Films deposited by ALD are extremely smooth, pinhole-free and conformal to the underlying substrate surface. This conformality enabled successful coating of powders, nanoporous membranes and high aspect ratio trench structures [6]. Furthermore, ALD is a low temperature process enabling deposition on thermally sensitive materials and established techniques exist for growing a variety of materials including oxides, nitrides and metals.

Figure 4 illustrates the atomic layer deposition process. Reaction A deposits a monolayer of chemisorbed species on the surface. Because the resulting surface is inert to precursor A, further exposure generates no additional growth. Next, precursor B is introduced. This molecule reacts with the product surface from the A reaction in a self-passivating manner. Consequently, the B reaction terminates after the completion of one atomic layer. If reaction B regenerates the initial surface, then the two reactions can be repeated in an ABAB... binary sequence to deposit a film of predetermined thickness.

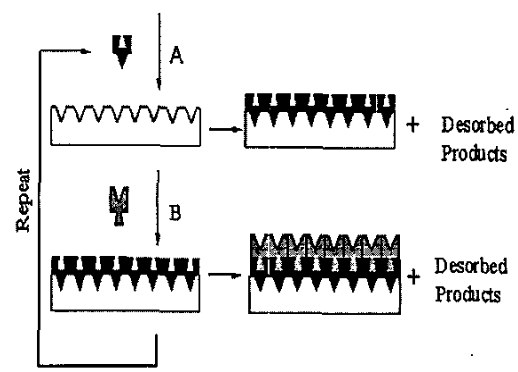


Fig. 4. Description of ALD process.

One example of this process is the atomic layer deposition of Al_2O_3 consisting of the following binary reaction sequence in which the asterisks designate the surface species:

A) $Al\text{-}OH^* + Al(CH_3)_3 \rightarrow Al\text{-}O\text{-}Al(CH_3)_2^* + CH_4$

B) $Al\text{-}CH_3^* + H_2O \rightarrow Al\text{-}OH^* + CH_4$

In reaction A, the $Al(CH_3)_3$ reacts with the surface hydroxyl groups to deposit a new monolayer of aluminum atoms terminated by methyl groups. In reaction B, the methylated surface reacts with H_2O vapor, thereby replacing the methyl groups with hydroxyl groups. CH_4 is liberated in both the A and B reactions. The net result of one AB cycle is the deposition of one monolayer of Al_2O_3 onto the surface.

An alloy consisiting of Al_2O_3 doped with ZnO can be deposited by implementing one additional cycle. In this cycle, two new species are added and the formation of ZnO within the Al_2O_3 layer is obtained. This will allow for extremely good control of the resisitivity in the final coated layer. By varying the ZnO content in the ZnO/Al_2O_3 layer the resisitivity can span approximately 20 orders of magnitude (see Figure 5). Such a dielectric layer could potentially dissipate the accumulated charge in electrostatic devices.

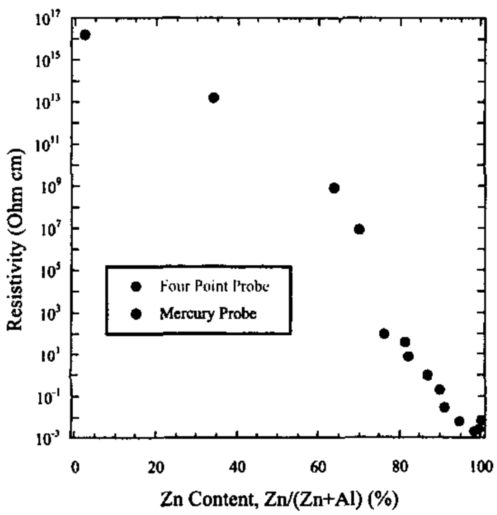


Fig. 5. Resitivity of ZnO/Al2O3 alloy as a function of percentage ZnO doping in the alloy.

III. MEMS Devices Protected by ALD

A. Mechanical Design and Fabrication

Figure 6 illustrates the design of the variable flip chip MEMS capacitor. The variable capacitor is constructed using the MUMPS technology provided by Cronos Corporation. This process includes three layers of polysilicon, two layers of oxide and one layer of gold [7]. The top plate of the capacitor consists of 2.0 μm poly-1, 0.75 μm layer of oxide, 1.5 μm layer of poly-2 and the final 0.5 μm layer of gold. The final layer of gold increases the conductivity and is also used for the bonding pads. The top plate is actually an array of 30 individual plates of equal area, which are connected to the bonding pads by springs of varying width.

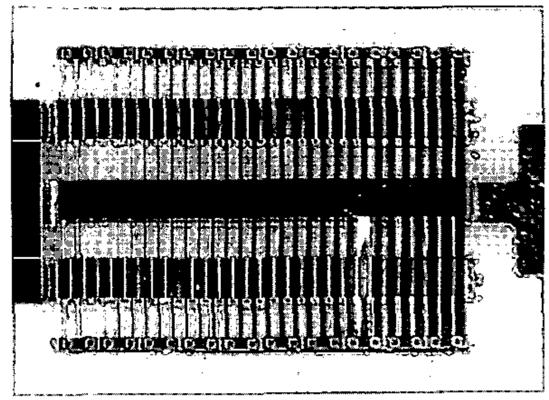


Fig. 6. Top view of the capacitor flip-chip mounted on a substrate after release and post processing. [8]

The variable capacitor is actuated using electrostatic forces between the top plate and the bottom plate. The electrostatic force exerted on each plate is uniform throughout the device. But, since each plate is connected to the bonding pad by a beam of different width (with different spring constant), the plates will snap down in a cascading manner [8].

The overall size of the device is 0.5x1.0 mm mounted on a receiving RF substrate (alumina) of 5x5 mm.

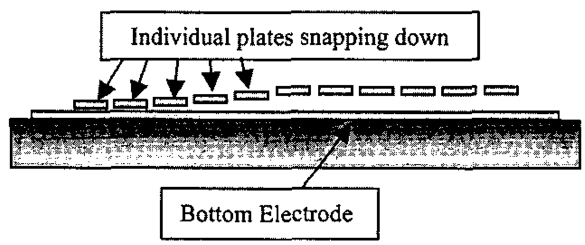


Fig. 7. Cross sectional view of MEMS capacitor and actuation principle. [8]

Following the flip-chip assembly and release [8], the device is coated with Al_2O_3 as described in the introduction section. The coating is done without any pre-treatment to the device and is carried out at a temperature of 177°C. This low temperature facilitates MEMS devices constructed from the MUMPS process where gold is the conductive layer. No other post-treatment is necessary following the ALD coating.

IV. Results

A. SEM Imaging

Cantilever beam test structures were coated with 60nm of Al_2O_3 and further investigated using Focused Ion Beam (FIB) and Scanning Electron Microscopy (SEM) techniques. One of the cantilever beams was cut using the

FIB and close up pictures of the Al_2O_3 layers were taken using SEM.

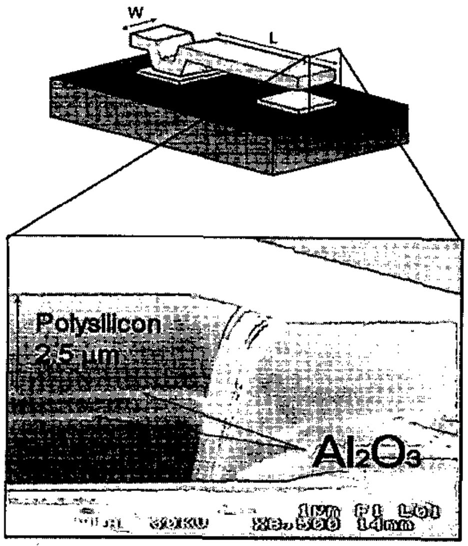


Fig. 8. Illustration of test cantilever and FIB cut depicting Al_2O_3 layer underneath suspended device[4]

B. *RF Testing*

The ALD coated variable MEMS capacitors are tested using a resonator connected to a HP 8510B Network Analyzer measuring from 300MHz to 3.0 GHz. The resonator exhibits a very high Q-factor, allowing the feasibility of accurate measurements of the coated MEMS devices. The MEMS device is connected to the resonator and a bias voltage is applied to actuate the device. The equivalent circuit for the test device is illustrated in Fig. 9.

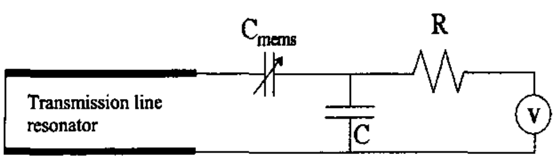
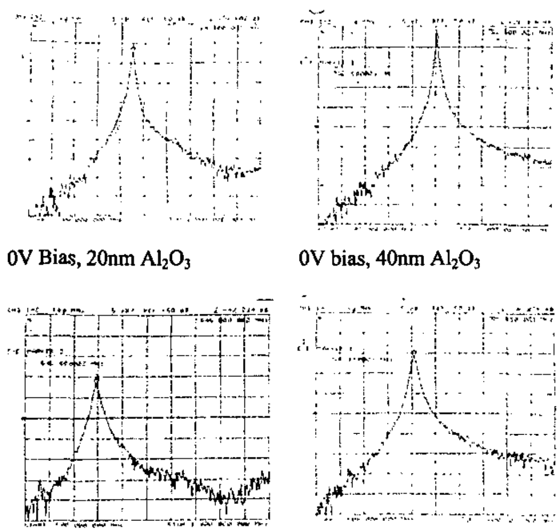


Fig. 9. Equivalent Circuit for testing the MEMS device [8]

All four figures in Fig. 9 represent actual measurements from the network analyzer. The two plots on the top depict the resonant frequency of the circuit with 20 and 40nm Al_2O_3 coated MEMS devices at 0Volts. The Q-factor for these devices is 104 and 145 respectively. The difference in the Q-factor can be explained by small differences in connecting the device to the resonator. As a DC bias voltage of 25Volts is applied, the resonant peak shifts, as is seen in the two lower plots. In the bias state, the top capacitor plates touch the lower electrode without shorting. This actuation would not be possible without a dielectric layer present.



0V Bias, 20nm Al_2O_3 | 0V bias, 40nm Al_2O_3

25V bias, 20nm Al_2O_3 | 25V bias, 40nm Al_2O_3

Fig. 10. Demonstration of shift in resonant frequency with applied voltage.

V. SUMMARY

RF MEMS variable capacitors devices have successfully been coated with Al_2O_3. This dielectric layer enables electrostatic actuation of the capacitors without shorting, whereas electrostatic actuation without a dielectric layer would not be possible.

VI. ACKNOWLEDGEMENTS

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