KELVIN PROBE MICROSCOPY FOR DIELECTRIC CHARGING ASSESSMENT IN SILICON NITRIDE FILMS FOR RF MEMS SWITCHES

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Abstract **— In this paper we present for the first time a systematic investigation for the dielectric charging in silicon nitride films for RF MEMS capacitive switches based on Kelvin Probe Force Microscopy. The effect of dielectric thickness has been first investigated through depositing SiN films with different thicknesses. Then, dielectric films have been deposited over thermally grown oxide, evaporated gold and electroplated gold layers in order to study the impact of the underneath physical layer over which the dielectric will be deposited. Finally, the effect of the deposition conditions has been investigated through depositing SiN films using low and high frequency PECVD method.**

Keywords: **Dielectric charging, Silicon nitride, Kelvin Probe Microscopy**

I – Introduction

RF-MEMS Capacitive switches are one of the most promising microelectromechanical systems (MEMS) devices for wireless applications. This is mainly due to their very high isolation and extremely low insertion loss. In spite of this, their transfer to the market still faces severe reliability problems nonetheless the research performed on the subject worldwide. Among these reliability issues, the charging of the dielectric is found to be the main obstacle for electrostatic actuated switches [1]. In contrast to the extensive study performed on this topic, a comprehensive understanding of the charging process in dielectric materials used in RF MEMS capacitive switches is still missing.

Different measurement setups have been applied on the way to assess the dielectric charging phenomena. Mainly, this has been performed through current measurements in Metal-Insulator-Metal (MIM) capacitors and capacitance and/or voltage measurements in MEMS capacitive switches. However, one major drawback for these approaches is the strong dependences of their results on the nature of the device under test. Thus, in MIM capacitors the presence of top electrode introduces interfacial charging and contributes to the discharge of injected charges while in MEMS the injected charges are collected through the bottom electrode in the up-state. Recently, the assessment of dielectric charging with Kelvin Probe Microscopy method has been introduced [2, 3] and found to be a very promising technique.

The main objective from this work is to present for the first time a comprehensive and systematic investigation on the charging process in SiN films based on Kelvin Probe Force Microscopy (KPM). The investigation took the advantage of the AFM tip to simulate the charge injection through asperities and then determine the surface potential induced at the SiN surface by injected charges. Both, the potential distribution and decay time constants have been investigated under positive and negative charge injection. The effect of dielectric thickness has been first investigated through depositing SiN films with different thicknesses. Then, dielectric films have been deposited over thermally grown oxide, evaporated gold and electroplated gold layers in order to study the impact of the underneath physical layer over which the dielectric will be deposited. Finally, the effect of the deposition conditions has been investigated through depositing SiN films using low and high frequency PECVD method.

II – Experimental Details

The SiN films that have been investigated in this work were deposited by PECVD method. In order to study the effect of the dielectric deposition conditions on the charging process, two deposition frequency modes have been used; low frequency (LF) power supply (380 KHz) and high frequency (HF) power supply (13.56 MHz). Five different test structures have been fabricated and are listed in table 1. The impact of the dielectric thickness has been investigated through samples S1 and S2. In both samples, LF SiN films with different thicknesses from 100nm to 500nm with 100nm step have been deposited over metallic layer (S1) and directly over bare silicon substrate (S2). Meanwhile samples S3, S4 and S5 represent SiN films that have been deposited for a real MEMS switch. In these three samples HF SiN films have been deposited over thermally grown SiO_2 (S3), evaporated gold (S4) and electroplated gold (S5) respectively. Figure 1 points out the exact locations of these three samples over a fabricated LAAS switch. Through S3, S4 and S5 samples the effect of the underneath physical layer over which the dielectric film will be deposited, has been investigated. Basically, this attempts to resemble the different scenarios of the charging process which take place in real MEMS switches where the dielectric layer is deposited over the metallic transmission line and extends in the coplanar waveguide slot.

In our KPM measurements, the AFM tip is used first to inject charges in the SiN surface and then determine the dielectric surface potential decay with

Table 1: *Layer structure of the samples under discussion.*

Layer	S1	S2	S3	S4	S5
SiN (nm)	100 → 500	100 → 500	500	500	500
Ti (nm)	-	-	-	50	50
Electroplated Au (µm)	-	-	-	-	2.5
Evaporated Au (µm)	500	-	-	200	200
Ti (nm)	100	-	-	50	50
SiO_2 (nm)	-	-	800	800	800
Silicon (µm)	500	500	400	400	400

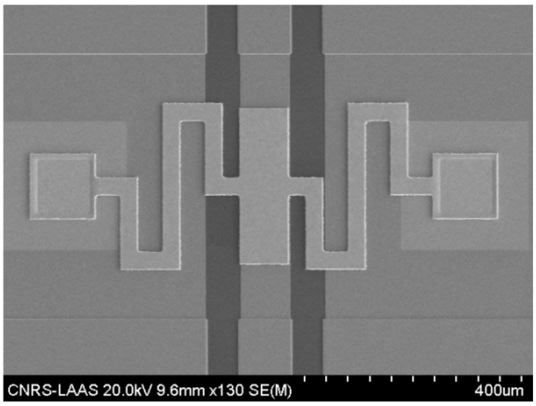

Figure 1: *Exact positions of S3, S4 and S5 samples over a fabricated LAAS MEMS switch.*

time. Both, the surface potential distribution and decay time constants have been investigated under positive (10V for 60sec) and negative (-10V for 60sec) charge injection. All the measurements have been performed in ambient air at room temperature using the Digital Instrument 3100 Nanoscope IV. SCM-PIT conductive tips which are Antimony n-doped silicon and coated with Cobalt-chrome have been used. Here it should be mentioned that the measured surface potential varies from one tip to another due to the difference in the intrinsic characteristics of each tip. Therefore, the same tip should be used in all measurements in order to be able to compare the results precisely. Finally, it should be pointed out that the KPM experiments have been performed several times for each sample and the error percentage in the results presented in this article is kept less than 1%.

III – Results and Discussion

A. Effect of Dielectric Thickness

The effect of dielectric film thickness has been studied by depositing LF SiN films with different thicknesses ranging from 100nm to 500nm with 100nm step. For each thickness, the nitride films were deposited on evaporated metal layers (S1) and on bare silicon (S2) (see table 1). The same potential has been applied to the AFM tip for all thicknesses which is (10V for 60 sec) for positive and (-10V for 60 sec) for negative charge injection.

Figure 2 presents the time dependence of the surface potential for samples S1 and S2 for the whole thickness range. As can be seen, the decay of the surface potential for the whole thickness range, independently of the substrate nature, is best fitted with the stretched exponential law, $\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right]$, where τ is the process time constant and β $(0\leq\beta\geq1)$ is the stretch factor. According to [4] the stretch factor represents an index of the charge collection complexity and the lower the value of β the more complex is the charge collection process.

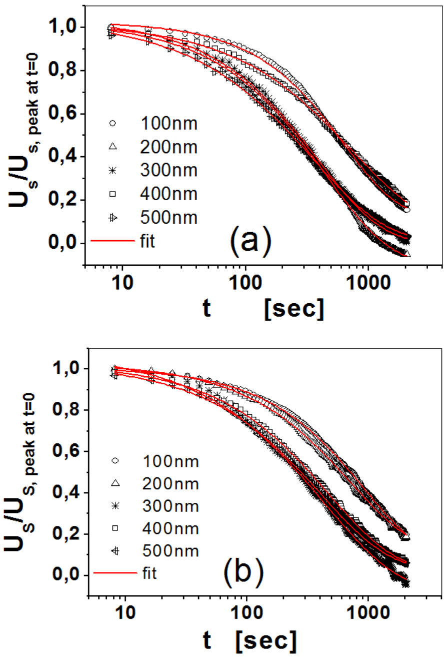

Figure 2: *Time dependence of the normalized surface potential to peak at t=0 for samples (a) S1 (b) S2.*

A summary of the time constants and the stretch factors for both S1 and S2 samples under positive charge injection is presented in figure 3. Regardless the substrate type, it is found that the time constant is always larger in the thinner dielectric films than in the thicker ones. Moreover, the stretch factor is larger in the thinner dielectric and lower for thicker one for both samples. The higher time constants in case of thin dielectric films can be attributed to the fact that the thinner material will be affected more by the defective first deposited SiN layers. Such a material will contain more complex defects with large capture cross section located deep in the band gap. In the case of the thick dielectric film on the contrary the top layers are expected not to be affected by these disordered bottom layers.

On the other side, the larger value of stretch factor for thinner dielectric films and the lower one for thicker films indicate that the relaxation law is related to the length of the path the charges have to travel before being collected by the bottom substrate. This leads us to the conclusion that the leading mechanism arises rather from a survival probability of a random walking particle in the presence of a static distribution of random traps [5]. In addition, the high value of stretch factor in the thin films supports the assumption of charge emission from a limited number of deep traps probably located deep in the band gap. On the other side, for thick dielectric materials where the effect of the first defective deposited layers is smaller the charging mechanism is expected to be simpler. The defects in these films are expected to exhibit simpler structure and have smaller capture cross section.

It can be observed from figure 3 that the time constants for dielectric films deposited directly over bare silicon (S2) are higher than the ones deposited over metallic layers (S1) for all thicknesses. On the other side, the stretch factor is almost the same for both S1 and S2 samples for all thicknesses, independently of the substrate nature. Finally, the decay time constants and stretch factors are asymmetric when positive or negative bias is applied for both S1 and S2 and for all thicknesses.

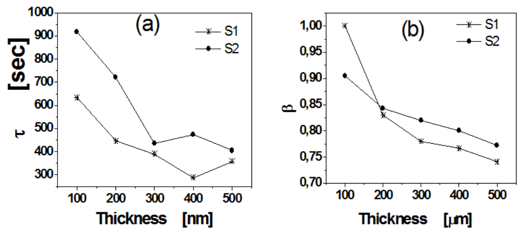

Figure 3: *The effect of the dielectric thickness on (a) time constant and (b) stretch factor for both S1 and S2 samples.*

B. Effect of Underneath layers

In order to study the effect of the underneath layer over which the dielectric will be deposited, HF SiN film was deposited over three different physical layers for a real MEMS switch (see table 1 and figure 1). In case of S3 samples, HF SiN films have been deposited directly over a thermally grown oxide. Hence, the effect of the formation of space charge region in the Si substrate on the charging process can be explored. Then, the effect of the roughness and the quality of the underneath metal layers have been investigated through depositing SiN films over evaporated gold (S4) and over electroplated gold (S5).

Figure 4 presents the normalized measured surface potential at t=0 for samples S3, S4 and S5. For both positive and negative charge injection, the potential distribution is wider in case of S3 samples (SiN over SiO2) comparing to S4 and S5 samples (SiN over metal). Besides, S4 and S5 have almost the same potential distribution. This effect is expected if we take into account that in S3 (i) there is a discontinuity in the dielectric film at the interface between the nitride and oxide films, which gives rise to the generation of an interfacial charge due to dielectric constant discontinuity and (ii) the effective thickness of the dielectric material is much larger due to the presence of the oxide film and the semiconductor space charge region, in case of no accumulation layer formation. All these lead to a lower and more disperse electric field distribution. When the bottom metal electrode exists (S4, S5) for the same potential applied to the AFM tip, the electric field becomes larger and more confined. The relatively small difference in the potential distribution between S3 on a side and S4 and S5 on the other side has to be attributed to the large thickness of the SiN film being used (500nm) which in sequence results in smaller electric field intensities for both cases.

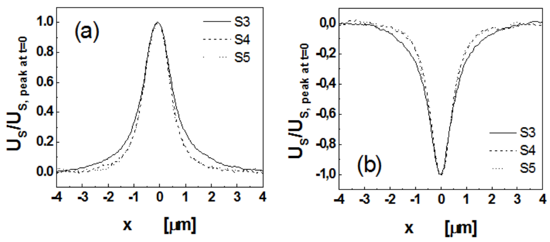

Figure 4: *Normalized surface potential at t=0 for samples S3, S4 and S5 under (a)positive and (b)negative charge injection.*

The time dependence of the measured surface potential is plotted in figure 5 for the three samples under both positive and negative charge injection. In all cases, the peak potential is found to decay exponentially with time following the stretched exponential law. From figure 5, the time constant is larger for S3 samples (SiN over SiO2) comparing to S4 and S5 (bottom metal electrode). However, the stretch factor is almost the same for all the three samples. These observations exist for both positive and negative charge injection. The almost similar values of the stretch factor for the SiN films deposited over the SiO2 and over the metallic layers indicate that the charging and discharging mechanisms doesn't relate to the bottom physical layer over which the dielectric film will be deposited. On the contrary, the time constant was found to be affected by the nature of the substrate on which the SiN film is deposited.

C. Effect of Deposition Conditions

The effect of the dielectric deposition method on the surface potential distribution is presented in figure 6. The differences in potential distribution are clearly small and can be attributed to the higher resistivity of HF SiN [5]. Here it must be emphasized that the LF material is more Si rich than the HF one, N/Si=0.79 and 1.04 respectively.

The authors would like to mention that the complete

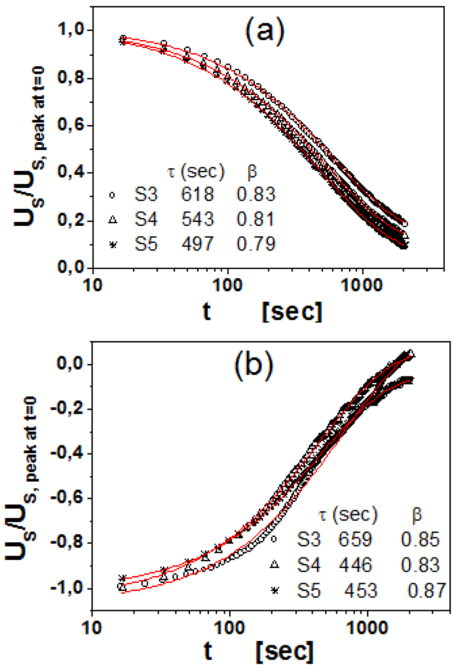

Figure 5: *Time dependence of the normalized surface potential to peak at t=0 for samples S3, S4 and S5 under (a)positive and (b) negative charge injection.*

analysis for the presented results will be presented in the final paper.

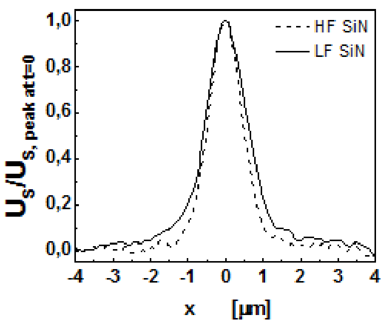

Figure 6: *Normalized surface potential at t=0 forS2 samples with 200nm HF and LF SiN films.*

IV – Conclusion

Dielectric charging process in silicon nitride films has been investigated based on Kelvin Probe Microscopy. SiN films were deposited with different thicknesses over different physical layers using both low and high frequency PECVD method.

In all cases, the surface potential was found to decay following the stretched exponential low. The decay time constant is mainly affected by the dielectric thickness and the substrate nature. Thinner dielectric films deposited over silicon substrate was found to have the highest time constants. On the other side, the stretch factor was found to be larger in thick dielectrics while it is not affected by the substrate type. Finally, both the time constant and stretch factors were found to be asymmetric when positive or negative charge injection is applied. The potential distribution was found to be wider in dielectric films deposited over silicon substrates than in the films deposited over metallic layers. In addition, the potential distribution was found to be more confined in thin dielectric films comparing to thick ones, independently of the substrate type. Finally, the material steochiometry was found to affect the charge distribution.

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