Implications of Rough Dielectric Surfaces on Charging-Adjusted Actuation of RF-MEMS

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Implications of Rough Dielectric Surfaces on Charging-Adjusted Actuation of RF-MEMS

Sambit Palit, Xin Xu, Arvind Raman, and Muhammad Ashraful Alam, Fellow, IEEE

Abstract—Actuation voltage shifts due to dielectric charging is a leading reliability concern in Radio-Frequency Micro-Electro-Mechanical Systems (RF-MEMS) capacitive switches. The inability to correlate dielectric surface roughness to charge accumulation makes predictive design difficult. We apply a sophisticated dielectric charging model on representative surfaces based on Atomic Force Microscopy (AFM) data, and show that there are significant, but predictable actuation voltage shifts due to surface roughness. The results suggest that surface roughness should be considered for accurate lifetime predictions, and simple metal-insulator-metal (MIM) capacitors may serve as a useful test structure for this phenomenon.

Index Terms—Surface roughness, dielectric films, RF-MEMS, reliability, leakage currents.

I. INTRODUCTION

The non-equilibrium kinetics associated with deposition of dielectric films or metal layers by Chemical/Physical Vapor Deposition (C/PVD), sputtering or epitaxial growth lead to intrinsically rough surfaces [1], [2] (Fig. 1a). The degree of roughness depends on the process conditions, i.e., temperature, pressure, time and reactant stoichiometry [3], [4]. Significant work exists on the stochastic modeling of deposition and growth processes for generating physically plausible surfaces [5], [6]. Surface roughness (SR) has also been related to dielectric capacitance either by spectral or fractal analysis, or by empirical parameterization using RMS surface roughness and asperity correlation lengths [7]–[9].

In some applications, electrostatic properties of a dielectric (not the details of the interface) dictate system operation, e.g., in Metal-Insulator-Metal capacitor (MIM-cap), see Fig. 1b. However, in case of Radio-Frequency Micro-Electro-Mechanical Systems (RF-MEMS) capacitive switches, an elastic electrode is suspended above the dielectric with an air-gap in between (Fig. 1c). This electrode can be pulled in electrostatically into contact with the rough dielectric surface (Fig. 1d). However, unlike a MIM-cap, this leaves air-gaps between the electrode and the dielectric. Some surface asperities may be compressed due to contact force exerted by the electrode during pull-in. We call the metal-dielectric contact in the MIM-cap case as a conformal contact (CC), and that of the pulled-in RF-MEMS switch as a rough contact (RC). When a bias voltage is applied between the two electrodes, charges are injected into electronic defects within the dielectric bulk, and remain temporarily trapped. These trapped charges reduce the actuation voltages ($V_{\text{act}}$) of the switch, and may lead to failure by stiction (switch remains pulled-in even when the bias is removed). Dielectric charging remains a leading reliability concern for RF-MEMS capacitive switches [10], [11].

The fabrication of MIM-caps requires fewer process steps than RF-MEMS switches. Therefore, dielectric charging is often first studied using leakage currents ($J$) in MIM-caps [12], [13], and the parameters obtained are used to model and predict actuation voltage shifts ($\Delta V_{\text{act}}$). However, it is widely believed that SR plays a significant role in charge trapping and leakage current behavior, and results obtained from MIM-cap measurements may not translate to an RF-MEMS switch if SR effects are excluded [14]. Even though the effects of dielectric SR on electrostatics and $V_{\text{act}}$ are well-studied [14], [15], we know of no work that correlates SR to charge accumulation, $J$, $\Delta V_{\text{act}}$, and reliability in RF-MEMS switches. In this letter, we explore the applicability of results derived from MIM-caps.

II. THEORY AND SIMULATION PROCEDURE

A. Surface Generation

Atomic Force Microscopy (AFM) measurements over the surface of PECVD Si$_3$N$_4$ dielectric were performed using the MFP-3D AFM (AsylumResearch), operated in the attractive regime of amplitude modulation AFM. Scans were done using cantilevers with typical stiffness of 25Nm$^{-1}$ at 90% set-point with the free vibration amplitude of 10–15nm, over an area of $L \times L$ with resolution of $N \times N$ pixels ($L = 1 \mu m$, $N = 1024$; additional details in [17]). An AFM surface scan ($Z_{\text{AFM}}(x, y)$) is shown in Fig. 2a. Dielectric SR can be
described by its Power Spectral Density (PSD) [18]

\[ Z_{AFM}^{2D}(f_x, f_y) = \frac{L}{2\pi N^2} \sum_{m,n=0}^{N-1} Z_{AFM}(x_m, y_n) e^{-2\pi j(f_x x_m + f_y y_n)} \], \tag{1}

where \( f_x \) and \( f_y \) take the values of 0, 1/L, 2/L, ..., N/2L. To create model surfaces that contain the equivalent spectral content as the AFM data, we calculate the effective 1-D PSD and then use it to generate random dielectric surfaces \((S_{gen})\)

\[ Z_{AFM}^{1D}(f) = \frac{1}{L} \sum_{j=0}^{N/2} \left[ Z_{AFM}^{2D} \left( \frac{j}{L}, f \right) + Z_{AFM}^{2D} \left( f, \frac{j}{L} \right) \right], \tag{2}\]

\[ S_{gen}(x) = F^{-1} \left[ \sqrt{Z_{AFM}^{1D}(f) F(n_g(x))} \right], \tag{3}\]

where \( F \) is the Fourier transform, \( F^{-1} \) is the inverse Fourier transform, and \( n_g \) is white Gaussian noise. \( S_{gen} \) is the randomly generated 1-D rough surface in a CC. To obtain the dielectric surface for an RC \((S_{cut})\), the protruding asperities are removed and flattened such that the metal touches the dielectric at few points corresponding to the flattened regions (see Fig. 2c). The ratio of the effective contact area to the total dielectric area for an RC is \( A_F \). For example, in Fig. 2c, we show a generated profile \( S_{gen} \) and the corresponding \( S_{cut} \) for \( A_F = 0.4 \). We also find that PSD of the dielectric is retained in \( S_{gen} \) and \( S_{cut} \), when compared against \( Z_{AFM}^{1D} \) in Fig. 2d.

### B. Dielectric Charging and Actuation Voltage Shifts

After the surface profiles are obtained, we solve the Poisson equation to compute electric fields \((E(x, z))\). Next, the steady state leakage current density at a position \( x \) on the surface – \( J_S(x) \), and the steady-state trapped charge density in the dielectric bulk – \( n_{T,S}(x, z) \) are determined [12]

\[ J_S(x) = \sum_{z=0}^{T_d} \frac{A_{IN}(x, z) A_E(x, z) N_T}{A_{IN}(x, z) + A_{OUT}(x, z) + A_E(x, z)}, \tag{4}\]

\[ n_{T,S}(x, y) = \frac{A_{IN}(x, z) N_T}{A_{IN}(x, z) + A_{OUT}(x, z) + A_E(x, z)}, \tag{5}\]

where, \( A_{IN}(x, z), A_{OUT}(x, z) \) and \( A_E(x, z) \) are the field-dependent current flux coefficients for charge injection, back-leakage and emission respectively, and \( N_T \) is the available trap density. The expressions of these coefficients, transient leakage current \((J(x, t))\), and trap occupancy \((n_T(x, z, t))\), are derived using the model described in [12]. The contribution to \( \Delta V_{act} \) due to trapped charges at position \( x \) is given by

\[ \Delta V_{act}(x, t) = \frac{q}{\epsilon_0 \epsilon_r} \int_0^{T_d} n_{T}(x, z, t) dz, \tag{6}\]

where \( q \) is the electron charge, \( \epsilon_0 \) is the permittivity of free space and \( \epsilon_r \) is the relative dielectric constant. The effective leakage current density \( J(t) \), and \( \Delta V_{act}(x, t) \) are calculated by taking the mean of \( J(x, t) \) and \( \Delta V_{act}(x, t) \) along the surface.

### III. Results

We compare the effects of charge trapping on \( J \) (Eq. 4) and \( \Delta V_{act} \) (Eq. 6) for both CC (MIM-cap system) and RC (pulled-in MEMS) of metal electrodes over a rough surface. We generate 100 random \( S_{gen} \) matching \( Z_{AFM}^{1D} \) of a real dielectric surface (Eq. 3), and create \( S_{cut} \) surfaces for 0.2 < \( A_F < 0.8 \). The Poisson equation is solved for each \( S_{gen} \) and \( S_{cut} \) to obtain \( E(x, z) \) and potential \((\phi(x, z))\) inside the dielectric. \( \phi(x, z) \) of one such surface for both CC and RC \((A_F = 0.4)\) are shown in Fig. 3a-b. In Fig. 3c, we plot electric fields at the dielectric-metal interface (which affects \( J \) into the dielectric) along the \( x \)-axis for both cases, and compare them to electric fields for planar dielectric surface of the same thickness. We see that
electric fields are significantly higher for the RC, compared to a CC. Also note that the fields for CC are comparable to a planar contact (PC) for much of the contact area.

Given $E$, $A_{IN}$, $A_{OUT}$ and $A_F$, typical calculated $J$ and $\Delta V_{act}$ for PC, CC and RC (surfaces depicted in Fig. 3a-b) are shown in Fig. 3d. The computed ratios of $J_S$ and $\Delta V_{act}$ of CC and RC ($A_F = 0.2$, 0.4, 0.6 and 0.8) to a PC for each surface are summarized in Fig. 3e. The average of $J_S$ ($x$) and $\Delta V_{act}$ ($x$) for all $x$ along a given dielectric surface characterizes the average current and expected actuation voltage shifts. We note that $J_S$ for CC is comparable to PC ($\#10$ in Fig. 3e); however, $J_S$ for RC is orders of magnitude higher ($\#6-9$ in Fig. 3e), reflecting the difference in respective electric fields (Fig. 3c). $\Delta V_{act}$ for RC is up to a factor of 10 larger ($\#1-4$ in Fig. 3e) than $\Delta V_{act}$ for PC and CC ($\#5$ in Fig. 3e). The enhancement of $J_S$ and $\Delta V_{act}$ in RC have a common physical origin – the asperities at the contact points. These enhancements are insensitive to $A_F$ since a few points dominate charge accumulation and injection. Relative increase in $J_S$ is higher than $\Delta V_{act}$ because only a fraction of injected charges are trapped.

IV. DISCUSSIONS AND CONCLUSIONS

We studied the effect of surface roughness (SR) of grown or deposited dielectric films on leakage current ($I_{leak}$) and actuation voltage shift (a $\Delta V_{act}$) in RF-MEMS capacitative switches due to dielectric charging. We generated random dielectric surfaces with spectral properties similar to real PECVD deposited Si$_3$N$_4$ surfaces, and compared $J_S$ and $\Delta V_{act}$ of MIM-cap and pulled-in RF-MEMS structures to idealized planar equivalents with no SR. We find that $J_S$ and $\Delta V_{act}$ for conformal contact MIM-cap are comparable to those of a planar contact. In contrast, $J_S$ of rough contact RF-MEMS pulled-in switch is orders of magnitude higher than that a planar contact, and $\Delta V_{act}$ is higher by an order of magnitude. This observation is true across all generated surfaces, irrespective of voltage bias and effective contact areas. We conclude that charging and leakage behavior in MIM-caps may therefore be modeled using planar contacts. Moreover, charging behavior assuming planar contacts (or characterized from MIM-caps) provide useful and approximate lower bounds to estimate dielectric charging effects in RF-MEMS. MIM-caps therefore prove to be useful test structures to study dielectric charging (but not leakage currents) in RF-MEMS capacitative switches.

Finally, a note regarding the validity of our computational approach: we used Fourier spectra to characterize SR; a wavelet-based decomposition could be more efficient as fewer coefficients would capture the asperities that dictate charging and leakage - this will be explored in a future study. The discussed approach (exact-2D surface reduced to quasi-1D using Eq.1-3) simplifies computation but does not affect the key conclusions – this assertion can be demonstrated by solving the Poisson equation (using a semi-analytical approach [9]) in quasi-2D and exact-3D structures. We also find that the tunneling of electrons through air-gaps in a rough-contact (using the model in [19]) are significantly lower than $J_S$ across all voltages, $A_F$ and generated surfaces used in this study (see Fig. 4). Although this additional tunneling component should be calculated for accuracy, our conclusions remain unaffected by its inclusion.

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