Effects of Surface Properties on the Effective Electrical Gap of Microelectromechanical Devices Operating in Contact

E. K. Chan and R. W. Dutton
CISX 305, Center for Integrated Systems
Stanford University, Stanford, CA 94305-4075
Email: edward_chan@stanfordalumni.org

ABSTRACT

The effective electrical gap between two conducting surfaces sandwiching a thin dielectric layer varies with applied voltage and pressure. Improved methods for measuring and modeling this variation are presented. Optical surface profile measurements of fixed-fixed beams, and capacitance-voltage measurements of a center-tethered structure that eliminates zipping are shown. A compressible contact surface model is used in 2-D simulations of electrostatically actuated beams to capture the surface effects. The simulation fit is good at low voltages but deteriorates at higher voltages. Substrate curvature and electronic effects are investigated but found to be negligible.

Keywords: *contact, surface, compressible, capacitance, electromechanical*

1 INTRODUCTION

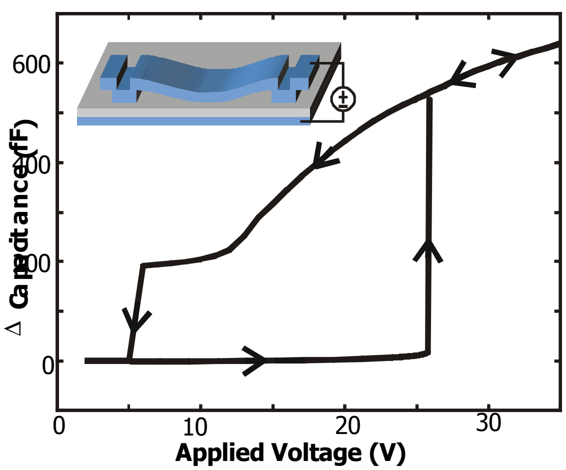

Fig. 1: Typical CV curve. Beam is shown in inset.

A typical electrostatically actuated device fabricated in MUMPs [1], consisting of a beam suspended above a dielectric-coated substrate, is shown in Fig. 1. Beyond the pull-in voltage, the polysilicon beam contacts the underlying silicon nitride layer creating a dielectric sandwich. The capacitance-voltage (CV) characteristic (Fig. 1) provides insight into contact mode behavior – a mode of operation important to capacitive microwave switches [2] and electrostatically actuated test structures operating in contact [3].

The fundamentals of CV measurements and simulations were presented at MSM98 [4] and further expounded in [5]. This work highlights improvements in measurement techniques and test structures, conclusively demonstrating the compressibility of the contact surfaces. A compressible contact surface model used in 2-D simulations of electrostatically actuated beams captures the surface effects at low voltages but deteriorates at higher voltages. Electronic and substrate curvature effects are investigated but found to be negligible. The profiles of beams of various lengths together with the spacing between the CV curves suggest that the effective gap for capacitance might be different from the effective gap for electrostatic forces.

2 MEASUREMENTS

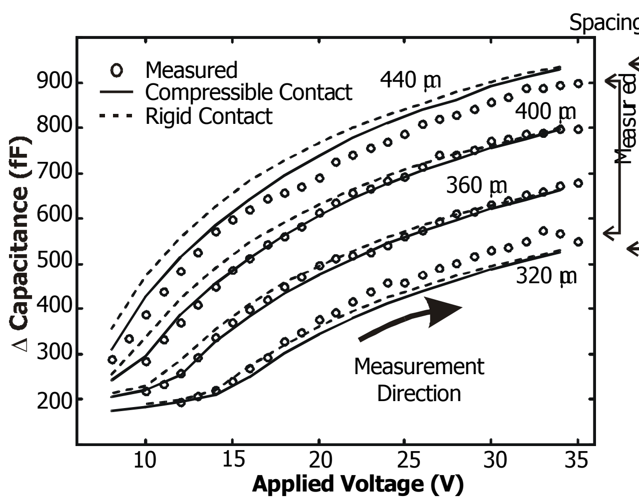

Fig. 2: Measured and simulated CV curves.

The CV measurements of four beams of different lengths were made as the beams were zipping up (as indicated in Fig. 2) to avoid charging issues [5]. The beams, fabricated in MUMPs29, were 1.97 µm thick and suspended 1.79 µm above the nitride. Capacitance measurements of a POLY0 pad on nitride show that the nominal electrical thickness of the nitride is 0.077 µm. Using the calibration procedure detailed in [6], Young's modulus is 140 GPa and the residual uniaxial compressive stress is 4.83 MPa. As Fig. 2 reveals, the simulation model in Abaqus [4], assuming a perfectly rigid contact surface, captures the CV trend correctly but the magnitudes are somewhat off. No single set of simulation parameters can match the measured data for all four beams accurately. While the exact values differ from fabrication run to fabrication run, the qualitatively similar discrepancy between measurements and simulations has been observed consistently [4], [5].

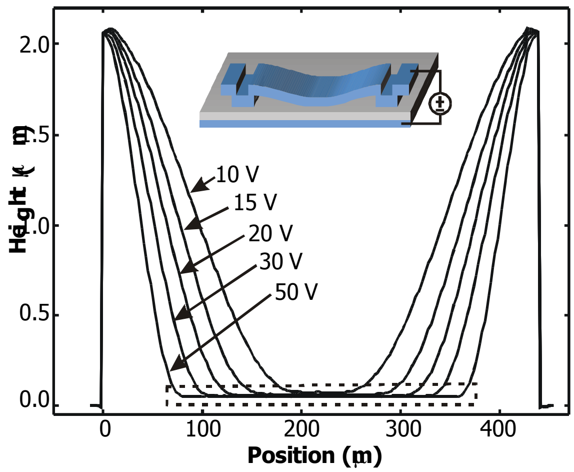

Fig. 3: Profile of beam zipping up.

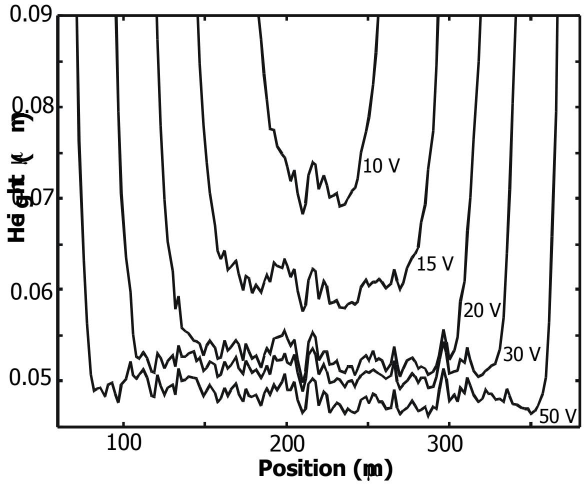

Fig. 4: Closeup of profile of beam in contact.

Zygo surface profile [7] measurements of the zipping up of a 440-µm-long beam are shown in Fig. 3 along with a close-up of the portion of the beam in contact with the nitride (in dotted-line box) in Fig. 4. Height is referenced to the POLY0 layers. Once in contact, the beam continues to move further downward towards the nitride as the voltage increases, moving about 20 nm from 10 to 30 V. Further penetration beyond that is limited, implying that contact with the "actual" rigid surface is made. This indicates some compressibility of the contact surface and hence variability in the effective gap of the silicon nitride. The excellent repeatability of the roughness measurements indicate that the measurement resolution is above the noise floor. Each profile measurement, each made at exactly the same site, was carefully leveled to consistent reference points so that the profiles could be compared directly. Unfortunately, capacitance and surface profile measurements could not be made simultaneously because the LCR meter and the Zygo profiler are located in separate rooms.

CV measurements of a test structure consisting of a POLY1 beam suspended above the silicon nitride surface by POLY2 tethers, as shown in Fig. 5, provide yet another perspective into the source of these discrepancies between measurements and simulations. After the beam is pulled-in for the first time, surface adhesion forces prevent it from springing back up. Theoretically, no zipping should occur after contact because the tethers are connected only to the center of the beam, and the beam was measured to be already flat within 0.01 µm even with no applied voltage. Yet, the capacitance-voltage plot of Fig. 6 reveals that the effective electrical gap of this structure still varies significantly with applied voltage.

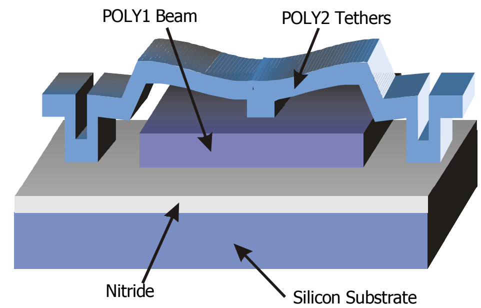

Fig. 5: Center-tethered surface measurement test structure.

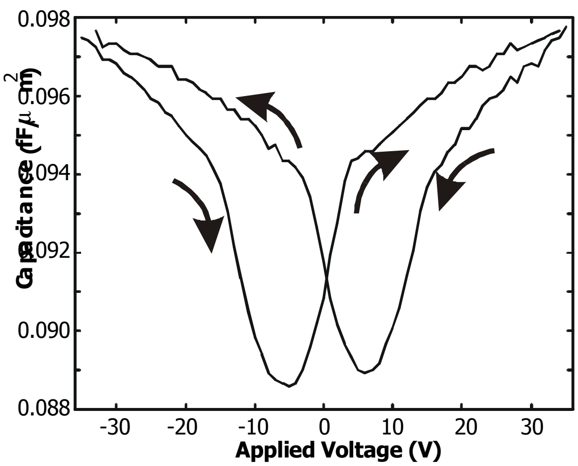

Fig. 6: Measured CV of center-tethered structure.

The illustrative close-up of the contact surface shown in Fig. 7 suggests that surface residue together with asperities might increase the effective gap between the beam and nitride surface, and hence the substrate. Since polysilicon is a hard material, the asperities themselves are unlikely to deform but the regions between the highest asperities can deflect closer towards the substrate. The CV data is converted into the surface stiffness vs. effective electrical gap data of Fig. 7 assuming a parallel plate capacitor model. The surface stiffness, which is assumed to be roughly equal to the reaction to the electrostatic pressure, is proportional to the applied voltage and inversely proportional to the square of the effective gap. This surface reaction pressure does not describe the hardness of any particular material but is the effective hardness of a surface speckled with residue and asperities, much like the stiffness of a bed surface is the hardness of an array of steel coils distributed under the surface and not the hardness of steel itself. For comparison, atmospheric pressure is 1×10^5 Pa.

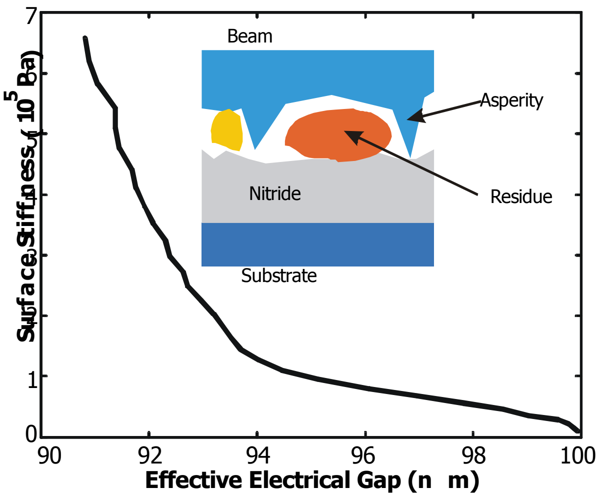

Fig. 7: Surface stiffness as a function of effective electrical gap. Schematic of surface residue is shown.

3 MODELING AND SIMULATION

The contribution of electronic effects to the measured CV characteristic is investigated via Medici [8] simulations. The high frequency CV characteristics of a polysilicon-nitride-silicon capacitor is shown in Fig. 8. The three curves are of cases where the capacitor system consists of

1. only the beam, nitride and substrate
2. the beam, surface layer, nitride and substrate, and
3. the beam with a connection to a p-well, surface layer, nitride and substrate.

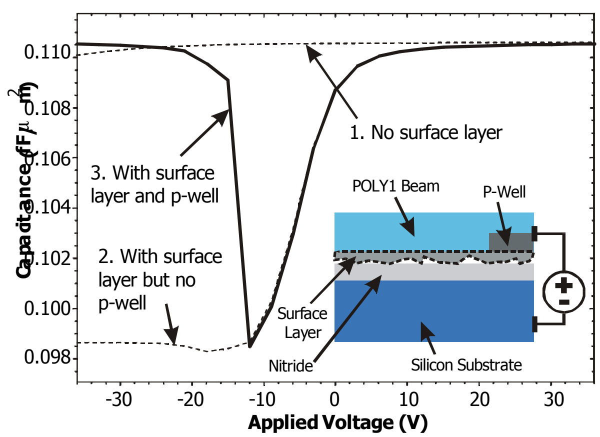

Fig. 8: Simulated CV of poly-nitride-silicon system. Layer configuration is shown in inset.

In the simulations, the beam and substrate are heavily doped with 5×10^{18} cm^{-3} dopants whereas the surface layer is lightly doped with 5×10^{16} cm^{-3}. Such a surface layer could be due to dangling bonds on the unpassivated surface of the beam after the HF release. The first CV curve is almost flat since depletion does not occur in the heavily-doped semiconductors. This CV characteristic was observed for POLY0 pads deposited directly on the nitride. Depletion of the surface layer causes the capacitance to drop in the second case. Only the third case, with a p-well, produces a CV that is similar to that measured for the center-tetherd structure. However, this scenario is unlikely because the p-well will have to be connected to the portion of the beam that is in contact with the nitride in order to provide inversion charge at high frequencies. No p-type dopants were introduced into the system during fabrication. Hence the observed variation of capacitance with voltage must be due, at least primarily, to mechanical effects.

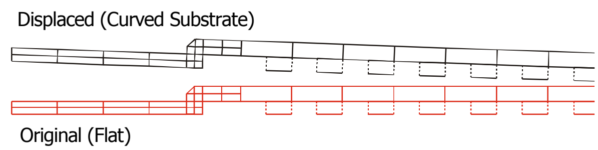

Fig. 9: Abaqus model including substrate curvature.

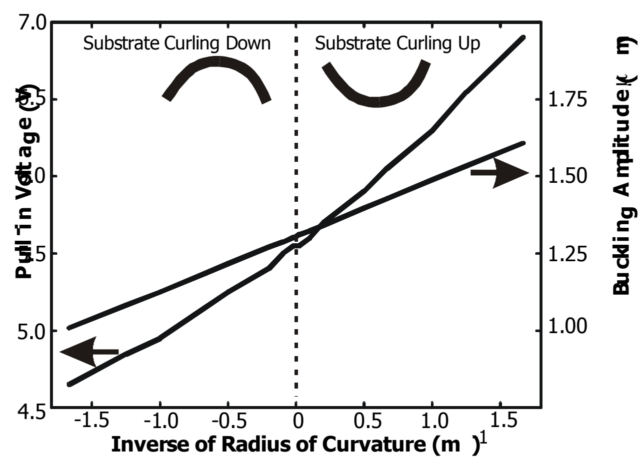

Fig. 10: Variation in buckling amplitude and pull-in voltage with substrate curvature.

The Abaqus 2-D simulation model of fixed-fixed beams that includes the effects of substrate curvature is shown in Fig. 9. The lower mesh is of the initial structure whereas the upper mesh is of the structure displaced corresponding to a change in substrate curvature. The change of substrate curvature changes the buckling amplitude and pull-in voltage of long fixed-fixed beams as shown in Fig. 10. When an originally-flat substrate curls up to a radius of curvature of 0.6 m (corresponding to an inverse radius of 1.6 m^{-1}), the buckling amplitude of a 700-µm beam increases by 0.3 µm whereas the pull-in voltage rises by over 1.0 V. The effect of substrate curvature on the capacitance of the shorter beams studied here is negligible, however. The portion of the beam in contact with the nitride varies in concert with the variation in substrate curvature, resulting in no net effect on the effective electrical gap.

With the apparent compressibility of the contact surface included in simulations, the fit is good at low voltages but deteriorates at higher voltages as shown in Fig. 2. In particular, the spacing in capacitance between the beams of different lengths is larger in simulations that in measurements.

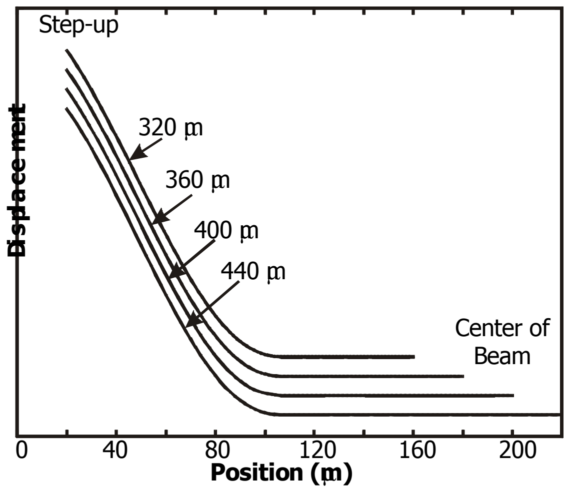

Fig. 11: Similar beam profiles near stepup.

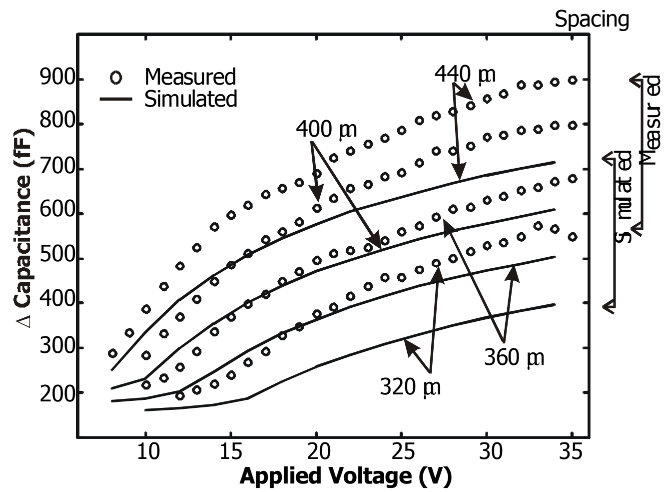

Fig. 12: Simulated CV with larger effective gap.

The simulated profiles of the left halves of four beams of different lengths, at the same applied voltage (34 V), are shown in Fig. 11. The profiles, which would otherwise all overlap, are offset vertically from one another. The profiles near the stepups are exactly the same, indicating that differences in capacitance between beams at any given voltage are directly proportional to the differences in beam lengths only. As a result, the spacing between the CV curves of any two beams should be constant with voltage beyond 20 V. The thickness of the nitride computed from the measured capacitance spacing is 0.097 μm. Using this value for nitride thickness produces the simulated curves of Fig. 12. The fit is poor except that the simulated spacing between the CV curves matches the measurements. This suggests that the effective gap for capacitance could be larger than the effective gap for electrostatic force. This might be due to a parasitic series capacitance near the surface layer that effectively reduces the magnitudes of all the measured capacitances.

4 CONCLUSIONS

Optical measurements conclusively show that the effective electrical gap between two conductors sandwiching a dielectric decreases with increasing applied voltage, probably due to compression of surface residue. A center-tethered test structure further confirms that the capacitance between two surfaces in contact varies with applied voltage. A compressible contact surface model improves the simulation fit to measurement but still fails to capture the behavior at high voltages. The profiles of beams of various lengths together with the spacing between the CV curves suggest that the effective gap for capacitance might be different from the effective gap for electrostatic forces. Simultaneous measurements of the variations in capacitance and beam profiles with voltage should shed more light on this discrepancy.

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