

# Characterization of Electrostatically-Actuated Beams through Capacitance-Voltage Measurements and Simulations

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## ABSTRACT

Detailed 2D electromechanical simulations of electrostatically-actuated beams reveal phenomena not captured by 1D or quasi-2D simulations. The behavior of the beam when in contact with a dielectric layer is studied. Capacitance-voltage measurements are used to extract material properties and explore surface phenomena such as charge accumulation, stiction and surface roughness. Monte Carlo simulations reveal the limits of simulation accuracy due to statistical distributions of input parameters.

**Keywords:** electrostatically-actuated beams, capacitance-voltage, contact, simulation accuracy

## INTRODUCTION

Electrostatically-actuated beams (Fig. 1) are widely used and studied in the MEMS community. Such beams are used as switches and resonators, and for extracting material properties [1,2,3]. Often, rather ad hoc "correction factors" are required to account for behavior not captured by simplified 1D or quasi-2D simulation models. These correction factors are usually specific to the particular process and range of beam dimensions being studied. Simulation results are presented using a more detailed 2D mechanical model which reveals some phenomena neglected by 1D or quasi-2D simulations.

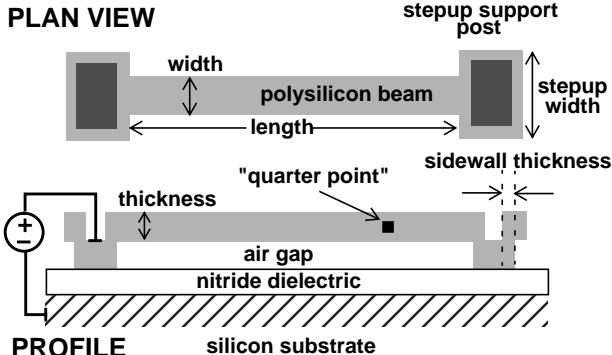


Fig. 1. Electrostatically-actuated beam

The behavior of the system is studied for the case when the beam is in contact with the nitride dielectric that coats the bottom electrode -- a mode of operation important to capacitive microwave switches [4]. Capacitance-voltage (CV) measurements are used to extract material properties and explore surface phenomena such as charge

accumulation, stiction and surface roughness.

Monte Carlo simulations reveal the limits of simulation accuracy due to the limited precision of extracted parameters. The distribution of beam pull-in voltages due to process variations is also studied.

## SIMULATION MODEL

Fig. 1 shows both a plan view and a profile of a typical electrostatically-actuated beam. Applying a voltage between the beam and silicon substrate causes the beam to deflect downwards. Fig. 2 shows a typical simulation of the capacitance between the top and bottom electrodes as a function of applied voltage with regions numbered corresponding to those in Fig. 3. Fig. 3 is a schematic plot of the total energy of the electromechanical system as a function of voltage and the displacement of a "quarter point" midway between the support post and center of the beam (see Fig. 1). The numbered circles indicate the displacement at equilibrium. As the voltage is increased, the characteristic "pull-in" phenomenon occurs when the barrier between the two minima disappears at the pull-in voltage ( $V_{pi}$ ) and a portion of the beam comes into contact with the surface of the dielectric. As the voltage continues to increase, more of the beam contacts the dielectric i.e. the beam "zips up". When the applied voltage is decreased, the quarter-point moves away from the surface, i.e. the beam "peels off", but still remains in the same local energy minimum region. Eventually, the barrier between the minima disappears and the entire beam pops off the surface of the dielectric.

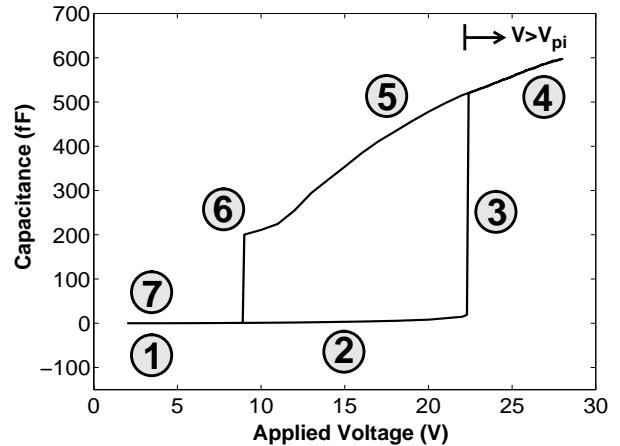


Fig. 2. Typical capacitance-voltage curve

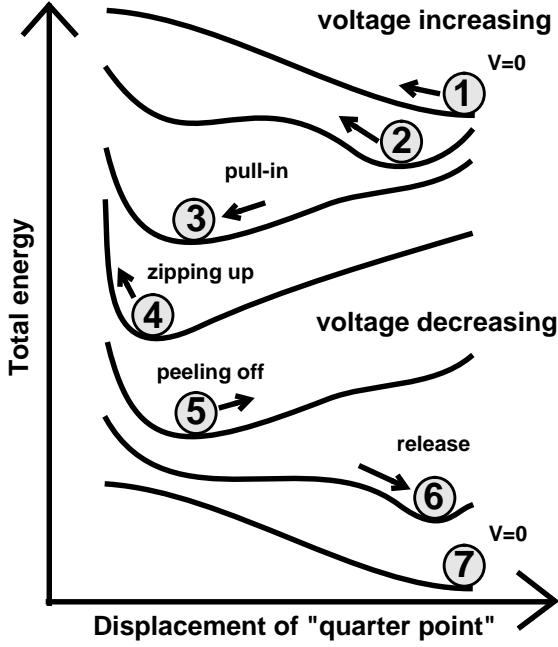


Fig. 3. Total energy of system and equilibrium state as a function of voltage and displacement of "quarter-point"

This electromechanical system is simulated in Abaqus with the electrostatic force applied to the bottom surface of the beam as a user-defined load [5]. The 2D Abaqus simulation provides good mechanical accuracy by automatically including the effects of geometric nonlinearity (or stress stiffening), compliant stepups and contact. The Abaqus model (Fig. 4) uses reduced-integration elements, with plane strain elements for the stepup which adheres to the dielectric surface, and plane stress elements for the beam itself. For the analysis, using 50 quadratic rectangular elements for one-half of the beam provides good accuracy. A correction factor to account for 3D plate-like effects in the beam is included [3].

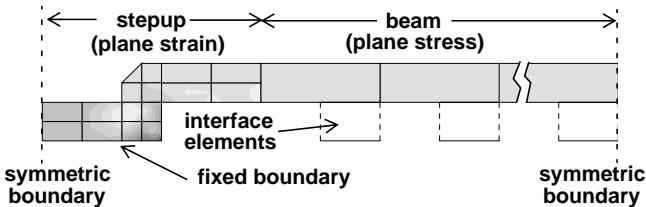


Fig. 4. Mechanical model in Abaqus

To model the electrostatic force, we assume that the beam is made up of many parallel-plate capacitors connected in parallel. This approximation is quite accurate for planar systems, particularly when the gap between electrodes is small as is the case when the beam is in contact with the dielectric. Effects of fringing fields [2] and finite plate thickness are included in our electrostatic force model. Results shown in Fig. 5 using a 2D field solver reveal the amount by which an ideal 30 $\mu\text{m}$ -wide capacitor model with

infinitely thin plates and no fringing fields underestimates the force between the plates.

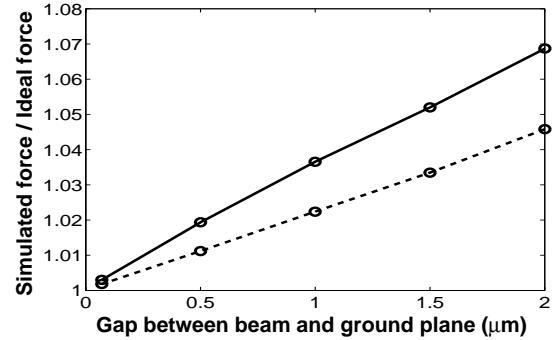


Fig. 5. Simulated electrostatic force on 30 $\mu\text{m}$ -wide beam

Fig. 6 compares the accuracy of a 2D Abaqus simulation to a 3D simulation done in IntelliCAD. The IntelliCAD model comprises a 400 $\mu\text{m}$  x 30 $\mu\text{m}$  beam 2 $\mu\text{m}$  thick suspended 2 $\mu\text{m}$  above a 0.6 $\mu\text{m}$  nitride layer. The ends of the beam are perfectly fixed. The beam is made up of 14 x 2 x 1 quadratic brick elements. The same dimensions, material properties, boundary conditions and discretization sizes are used in the 2D Abaqus simulation. The IntelliCAD model, which consumes over three orders of magnitude more computation time, is just a little stiffer (less than 2%).

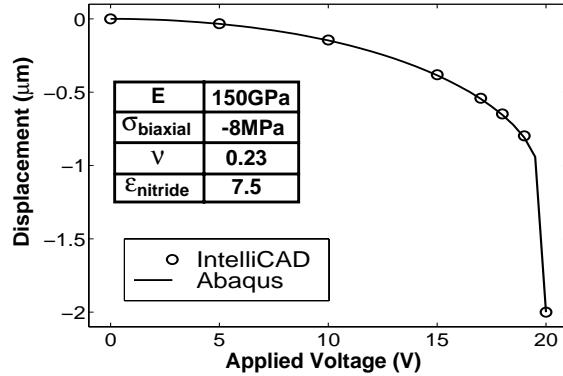


Fig. 6. Comparison between Abaqus model and IntelliCAD

We choose to quantify the residual stress in the system in terms of an expansion coefficient,  $\alpha$ . The resultant compressive biaxial residual stress in a uniformly deposited film due to this coefficient is

$$\sigma_{biaxial} = \frac{\alpha E}{1 - \nu} \quad (1)$$

where  $E$  is the modulus of elasticity and  $\nu$  is Poisson's ratio. This allows us to gradually ramp the system up to the correct initial stress state before applying an electrostatic load. Incorporating a large residual stress as an initial condition in a single step can result in erroneous simulations -- underestimating the initial bowing or deforming the beam into an incorrect buckling mode.

The average longitudinal initial stress in the beam depends on the length of the beam, the width of the stepup and the sidewall thickness (Fig. 7). The width of the stepup used in 2D simulations should be less than the actual physical width because only the portion of the stepup that is close to the beam interacts with the beam. In general, the stress relaxes more for more compliant stepups and longer beams. However, with the 30 $\mu\text{m}$ -wide stepup, the stress actually increases with beam length.

The stiffness of the stepup affects the initial shape of the beam. The interferometric picture (Fig. 8) reveals that beams of the same length can either bow up or down depending on the width of the stepups. A beam with a narrow stepup (90 $\mu\text{m}$ ) as shown at the top of Fig. 8 bows up whereas beams with wide stepups bow down. The three beams at the bottom of Fig. 8 are part of an array of 10 parallel beams all connected to the same stepup structure. The beam at the edge of the array (second from the top), which has an effectively narrower and hence more compliant stepup, bows up whereas the two lower beams bow down. This effect of stepup widths is verified in simulations and implies that beams connected to the same support posts can influence each other mechanically if their separations are small enough. In some cases, beams which bow up initially do not return to that initial state after going through a pull-in-and-release cycle but remain bowed down.

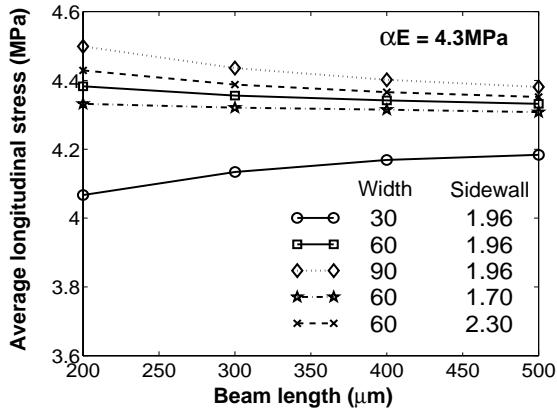


Fig. 7. Average longitudinal stress in beam as a function of stepup geometry and beam length

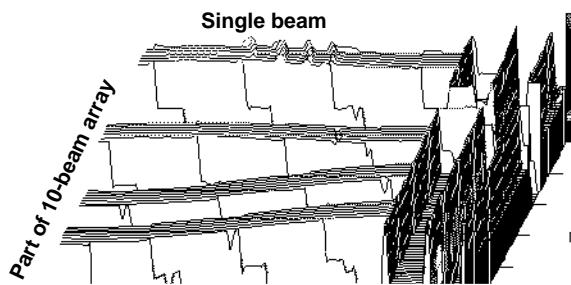


Fig. 8. Interferometric image of 540 $\mu\text{m}$  fixed-fixed beams, courtesy of Zyglo Corporation

## OPTICAL AND MECHANICAL MEASUREMENTS

Fixed-fixed beams and cantilevers of various dimensions were fabricated in the POLY1 polysilicon layer on the MUMPs 22 run. A Zyglo interferometer was used to survey the structures and showed that the fixed-fixed beams were flat (less than 0.03 $\mu\text{m}$  of bow at the center) up until lengths of 520 $\mu\text{m}$ . 600 $\mu\text{m}$  beams bowed by 1.06 $\mu\text{m}$ . Cantilevers longer than 200 $\mu\text{m}$  curled down towards the substrate due to a stress gradient of about 0.4MPa/ $\mu\text{m}$ . Cantilevers longer than 290 $\mu\text{m}$  touched the nitride.

The thickness of the polysilicon was determined by an interferometric measurement of the thickness of a long polysilicon cantilever that was stuck to the nitride. The gap was determined by subtracting that thickness from the height of a short fixed-fixed beam above the nitride. For verification, a Dektak IIA was used to measure the thickness of a 600 $\mu\text{m}$  fixed-fixed beam pushed down by the force of the Dektak stylus, and the height of a 200 $\mu\text{m}$ -wide beam which was only partially released. The electrical thickness of the nitride (thickness divided by  $\epsilon_r$ ) was determined from a capacitance measurement of a polysilicon layer (POLY0) deposited directly on the nitride. This nitride thickness measurement neglects any overetch due to the etching of polysilicon and PSG layers [3]. Furthermore, when the beam comes into contact with the nitride, the surface roughness of the polysilicon effectively adds to the electrical thickness of the nitride because it determines the minimum separation of the two plates of the capacitor.

Table 1 shows the parameters used in simulations. Widths and lengths are assumed as drawn since linewidth resolution is better than 0.1 $\mu\text{m}$  [6]. Perfect conformal deposition is assumed, and Poisson's ratio is taken as 0.23.

Table 1. Parameters used in simulations

Poly thickness	Air gap	Nitride thickness	Poisson's ratio	Sidewall thickness	Stepup width
1.96 $\mu\text{m}$	1.94 $\mu\text{m}$	0.068 $\mu\text{m}$	0.23	1.96 $\mu\text{m}$	60 $\mu\text{m}$

## ELECTRICAL MEASUREMENTS

$V_{\text{pi}}$ 's, voltages at which the capacitances of the systems change abruptly, were measured using an HP4275A capacitance meter with voltage steps of 0.1V. The dice were placed in Gel-Pak<sup>TM</sup> trays. Measured  $V_{\text{pi}}$ 's are plotted on a semilog scale in Fig. 9 and lie on a straight line as expected. These measurements were confirmed by using an HP4155A to source a constant 20pA current and observing the voltage of the beam increase as a function of time. At pull-in, the capacitance increases abruptly and the voltage of the beam has to decrease momentarily due to charge conservation. The  $V_{\text{pi}}$ 's are significantly lower than measurements made on previous MUMPs runs [3] indicating that the polysilicon is more flexible.

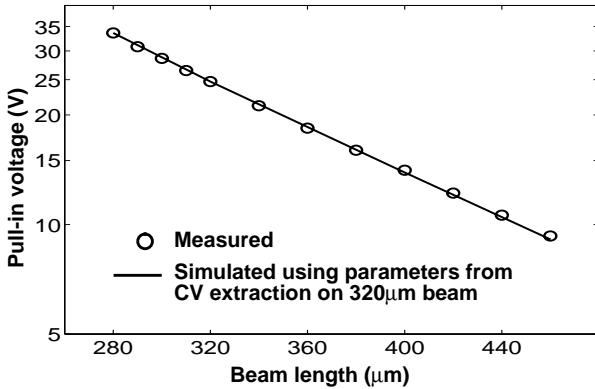


Fig. 9. Pull-in voltages as a function of beam length

Typical CV curves of a fixed-fixed beam and a cantilever are shown in Figs. 10 and 11 respectively. There is a plateau in the peel-off portion of the cantilever CV curve where most of the cantilever snaps off the nitride surface leaving only the tip touching as shown schematically in Fig. 11. This phenomena occurs only for certain cantilever lengths and has been verified in simulations.

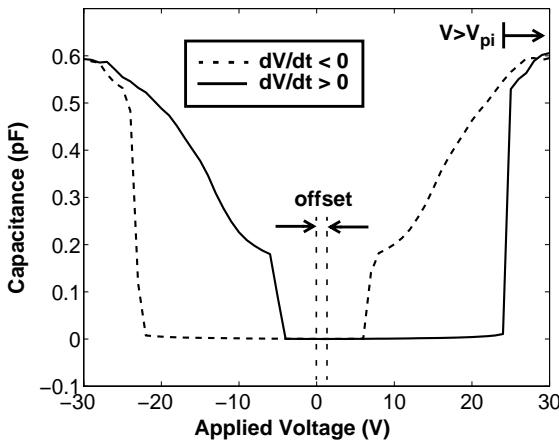


Fig. 10. CV curve of a 340μm fixed-fixed beam

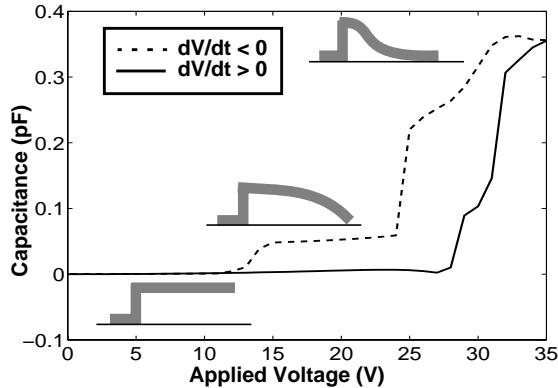


Fig. 11. CV curve of a 130μm cantilever beam

Stiction, which holds back the beam somewhat during peel-off, causes the zip-up and peel-off regions of the CV curves above  $V_{pi}$  not to overlap as they would otherwise (compare the regions  $V > V_{pi}$  in Figs. 2 and 10). Trapped charge in the nitride shifts the measured  $V_{pi}$ 's and offsets the CV measurements along the voltage axis as shown in Fig. 10. Assuming a sheet of nitride charge, the offset voltage is

$$V_{offset} = \frac{xQ_f}{\epsilon_0\epsilon_r} \quad (2)$$

where  $Q_f$  is the areal charge density,  $x$  is the distance of the charge sheet from the nitride-substrate interface and  $\epsilon_0\epsilon_r$  is the relative permittivity of the nitride. To quantify this charge, we measured  $V_{pi}$ 's by applying both positive and negative  $V_{pi}$ 's should be of the same magnitude since the electrostatic force is proportional to the square of the applied voltage. The measured differences between the magnitudes were less than 0.2V if we waited for more than 5 minutes between measurements. Thus, fixed charge is not a major problem.

Mobile charge, however, seriously distorts the measurements.  $V_{pi}$ 's measured in quick succession (less than 1 minute between measurements) are successively lower (magnitudes tending towards zero). This indicates that charge of polarity opposite to that of the voltage applied to the beam is being accumulated with each measurement.

Fig. 12 shows the measured capacitance of a beam as a function of time at a constant applied voltage. This particular 370μm long beam was stuck to the nitride even with no applied voltage, allowing us to measure the decay rate of the capacitance when the applied voltage was removed. The rate of capacitance increase is larger for higher applied voltages. The measurement shown is that using a 100kHz 50mVrms sensing signal but the measurement shows no dependence on signal amplitude or frequency.

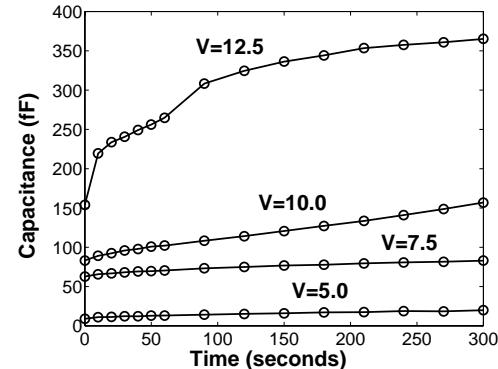


Fig. 12. Capacitance variation with time for various constant applied voltages

These measurements indicate that charge builds up in the system, probably in the nitride or near its surface,

when the beam is in contact with the nitride surface. The polarity of the charge is opposite to that of the beam thus attracting more of the beam into contact and increasing the capacitance of the system. Another source of charging effects could be the movement of charge from the bottom to the top surface of the nitride where it has the largest effect as shown by Eq. 2. The sensitivity of this system to surface charge could be exploited to monitor the movement and buildup of charge in dielectrics in real-time.

In order to avoid charge buildup, especially at high voltages, and to avoid stiction effects, we measure the capacitance of the beam quickly as it is zipping up instead of when it is peeling off. We assume that stiction is a very short ranged force which has no effect until two surfaces are in contact, and therefore does not influence the zipping-up process. While holding the voltage steady at a voltage well below pull-in but still high enough to hold the beam once the beam is in contact with the nitride surface, we induce contact by pushing the beam down with a probe tip. We then ramp up the voltage while measuring capacitance. The measurement takes about 10 seconds and is shown in Fig. 13 for a 320 $\mu$ m beam.

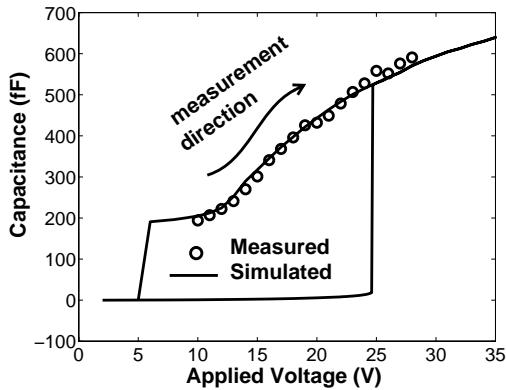


Fig. 13. CV curve of a 320 $\mu$ m beam

## MATERIAL PROPERTIES EXTRACTION

With geometrical measurements,  $V_{pi}$ 's and CV curves, E and  $\sigma_{biaxial}$  can be extracted. Fig. 14 shows contours of  $|V_{pi}^{measured} - V_{pi}^{simulated}|$  in E- $\sigma_{biaxial}$  space of a 320 $\mu$ m fixed- fixed beam. All simulations using E- $\sigma_{biaxial}$  pairs within the narrowest contour ( $\pm 0.1V$ ) give simulated pull-in voltages within  $\pm 0.1V$  of the measured value. Similar contours can be obtained for a beam of a different length and the region where the  $\pm 0.1V$  contours of the two beams overlap is the region in E- $\sigma_{biaxial}$  space which gives the correct value of  $V_{pi}$  for both beams. By overlaying the contours for 320 $\mu$ m and 440 $\mu$ m beams, and assuming a resolution in  $V_{pi}$  of  $\pm 0.1V$ , we obtain  $E=110 \pm 2.9$ GPa and  $\sigma_{biaxial}=-6.0 \pm 0.4$ MPa. The uncertainties in E and  $\sigma_{biaxial}$  increase to  $\pm 5.2$ GPa and  $\pm 0.8$ MPa respectively if

the  $V_{pi}$  resolution is only  $\pm 0.2V$ . The extracted E is low and could be due to a more porous microstructure.

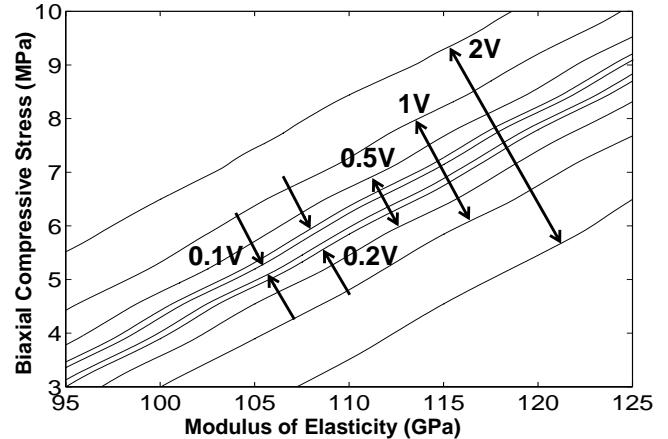


Fig. 14. Contours of  $V_{pi}$  resolution for 320 $\mu$ m beam

The RMS difference between measured and simulated capacitances gives another set of contours, shown in Fig.15, for the 320 $\mu$ m beam. These contours are more sensitive to E since the behavior of the beam when in contact with the nitride surface is dominated by bending. By overlaying this set of contours over the  $V_{pi}$  contours of Fig. 14, E and  $\sigma_{biaxial}$  can be determined from measurements of only one device. Noise in the present capacitance measurements force us to assume RMS errors of at least  $\pm 15$ fF. The extracted parameters are  $E=112 \pm 4.7$ GPa and  $\sigma_{biaxial}=-6.5 \pm 1.0$ MPa. These values are quite similar to that obtained using the previous method. Fig. 13 compares the measured capacitances to the simulated values.

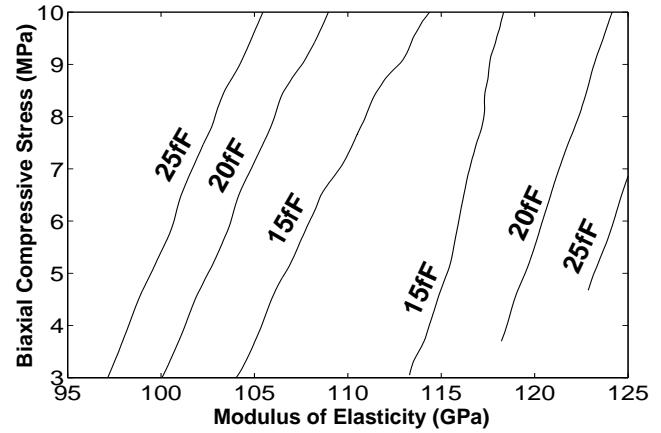


Fig. 15. Contours of RMS difference between measured and simulated capacitance values for 320 $\mu$ m beam

These parameters, extracted from a single device, are used to predict the behavior of beams of different lengths. Fig. 9 compares simulated  $V_{pi}$ 's to measured values whereas Fig. 16 compares simulated CV's to

measured curves for various beam lengths. The prediction of  $V_{pi}$ 's is reasonable but the CV fit is poor for the 400 $\mu\text{m}$  beam. A single set of simulation parameters could not fit all the measured CV curves even if the gap spacing and nitride thickness were varied arbitrarily. Surface roughness of the polysilicon might play a role here -- at the higher voltages used to measure the shorter beams, the roughness at the surface might be compressed so that the separation between the beam and substrate approaches the measured nitride thickness whereas at low voltages, the surface roughness increases the separation. Thus as shown in Fig. 16, the measured capacitances of the 400 $\mu\text{m}$  beam are lower than the simulated capacitances at low voltages but approach the simulated values at higher voltages.

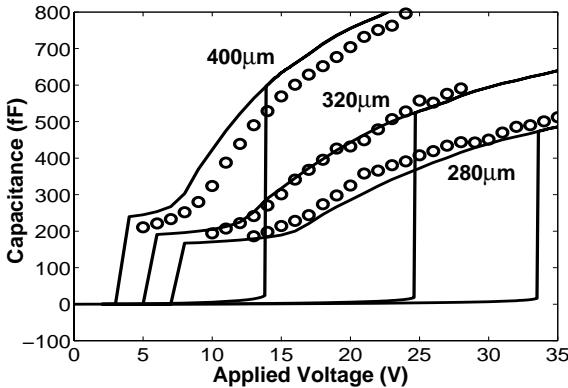


Fig. 16. Measured and simulated CV curves

## MONTE CARLO SIMULATIONS

In a complex non-linear system such as this electrostatically-actuated beam, it is difficult to determine the interdependence of various properties and parameters and hence Monte Carlo simulations are required. As a guide for users of MEMS simulation tools, a Monte Carlo simulation on a 320 $\mu\text{m}$  beam (measured  $V_{pi} = 24.7$ ) was performed to obtain bounds on the precision of the simulated  $V_{pi}$  assuming finite precision in input parameters as given in Table 2. The resolution of  $E$  and  $\sigma_{\text{biaxial}}$  are that described in the previous section whereas the resolution of the other parameters are assumed from experience with the measurement equipment. A Monte Carlo simulation assuming uniform distributions of the input parameters within their ranges of uncertainty gives a standard deviation in  $V_{pi}$  of 0.36V. The distribution of  $V_{pi}$ 's is shown in Fig. 17.

Table 2: Precision of input parameters

Polysilicon thickness	Air gap	Nitride thickness	E	$\sigma_{\text{biaxial}}$
$\pm 0.01\mu\text{m}$	$\pm 0.01\mu\text{m}$	$\pm 0.01\mu\text{m}$	$\pm 3\text{GPa}$	$\pm 0.4\text{MPa}$

The range of  $V_{pi}$ 's due to intra-run variations in process parameters can be determined assuming some reasonable

standard deviations in parameters given in Table 3 [3,6]. The resulting standard deviation in  $V_{pi}$  is 2.92 V.

Table 3: Standard deviations due to processing variations

Polysilicon thickness	Air gap	Nitride thickness	E	$\sigma_{\text{biaxial}}$
0.049 $\mu\text{m}$	0.12 $\mu\text{m}$	0.0024 $\mu\text{m}$	1.9GPa	0.45MPa

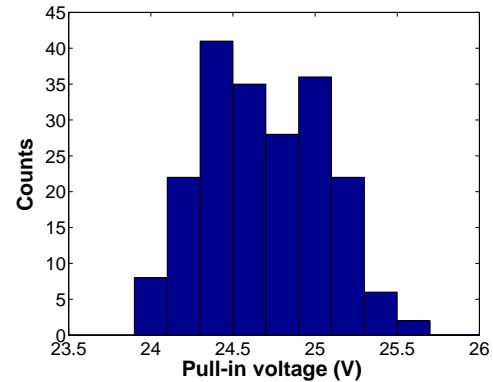


Fig. 17. Distribution of pull-in voltages due to finite precision of simulation parameters

## CONCLUSIONS

It is shown that detailed 2D mechanical models, particularly of stepups, reveal phenomena not captured by 1D or quasi-2D simulations. However, 3D simulations are necessary to model plate effects and the stepup supports more accurately. CV measurements of the beam in contact with the nitride surface can potentially be used for calibration if the effects of charge accumulation and surface roughness are mitigated. Currently, a process using a thicker oxide layer as a dielectric is being developed. Interferometric measurements will be used to corroborate the CV measurements and explore 3D effects.

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