Abstract — In this paper we are investigating the potential to employ small devices in crucial areas with limited volumes in electron microscopes. We present the analysis of the electric fields that are present in an electrostatically actuated micro electro mechanical systems (MEMS) device. The electric fields are modeled using finite elements methods (FEM). Preliminary results are shown from scanning electron microscope (SEM) measurements of an electrostatically actuated two degrees of freedom (2DOF) nanometer precision table. From the FEM results the influence of the electric fields on an electron beam traversing the devices can be calculated. This influence is calculated to be a trajectory displacement in the order of tens of nanometers for typical acceleration voltages. SEM measurements show significant vibrations in the images of non-movable parts of the devices when applying actuation voltages to the devices. This shows an effect of actuation on the detected electrons while imaging. Deflections up to 2.2 μm have been observed for a voltage of 80 V pp. This deflection cannot be fully attributed to deflections of the incoming beam. Therefore we include in a qualitative analysis the trajectory of emitted secondary electrons that are detected.

Keywords : MEMS, electron microscopy, electrostatic actuation, FEM

I - Introduction

We are investigating the potential to employ small devices in crucial areas with limited volumes in electron microscopes. For instance, we want to investigate if it is possible to position small apertures in the electron beam column.

To this end, micro electro mechanical systems (MEMS) devices could be used. For nanometer precise actuation in the plane of imaging, we use a two Degrees of Freedom (2DOF) manipulator with electrostatic comb drive actuation. [1]

It is clear however, that electrostatic actuation can potentially complicate the imaging of the electron microscope. Electric fields from the electrostatic actuator may influence the trajectory of the incoming beam or the amount and trajectory of secondary electrons that can be detected.

Therefore we decided to thoroughly investigate the influence of electrostatic actuation on the imaging of electron microscopes. Finite element modeling (FEM) has been used to calculate the relevant electric fields at and in the vicinity of our complex geometries and to calculate the effect on the electrons while they traverse the device. Furthermore we show preliminary results that indicate the effect of electrostatic actuation during Scanning Electron Microscopy (SEM) imaging.

SEM is used for imaging the MEMS devices and to visualize the actuation of the table. Another benefit of using SEM is that the effect of the actuation on the imaging can be visualized more easily at lower magnification, certainly because secondary electrons have a relative low energy. [2] Since low energy electrons are slow, they will be longer exposed to the electric field and thus be more deflected. We use their deflections to test our models.

II - Finite Element Modeling

The modeled geometry consists of a scanning table with an aperture in the center, see Figure 1. The table is suspended by four flexible beams. Electrostatic actuation of the table is performed by comb drives at the ends of the suspending beams. To simplify the geometry, only one simplified parallel plate actuator is considered. Table 1 shows typical length scales of this model. The point (0,0,0) is the center of the aperture, see the arrow.
Figure 2: The electric field in the aperture. The y-component $E_y$ (blue) and z-component $E_z$ (red) of the electric field are zero and thus overlap, the x-component $E_x$ of the electric field is shown in green.

Table 1: typical length scales of the modeled geometry

<table>
<thead>
<tr>
<th>Description</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap between parallel plates</td>
<td>$g$</td>
<td>3 μm</td>
</tr>
<tr>
<td>Diameter of aperture</td>
<td>$d$</td>
<td>50 μm</td>
</tr>
<tr>
<td>Length from gap to aperture</td>
<td>$L$</td>
<td>1140 μm</td>
</tr>
<tr>
<td>Height (z-direction) of device</td>
<td>$h$</td>
<td>50 μm</td>
</tr>
<tr>
<td>Thickness of beams</td>
<td>$t$</td>
<td>3 μm</td>
</tr>
</tbody>
</table>

In the model the electric fields have been calculated for a constant voltage on the actuator of 100 V. This voltage is the maximum actuation voltage for the device. The electric field in the aperture is investigated. Figure 2 shows the electric fields in the middle of the aperture in the x-direction. This figure shows that the y-component $E_y$ and z-component $E_z$ are zero, which is as expected from symmetry considerations. The x-component $E_x$ is negative for $x<0$ and positive for $x>0$, which means incoming electrons from an electron beam will be subject to a force towards the middle of the aperture. The same argument applies to the y-axis through the center of the aperture. On that axis the x-component $E_x$ and z-component $E_z$ of the electric field are zero and the y-component $E_y$ is the same as the x-component in Figure 2. This means that a distribution of emitted secondary electrons coming from the device will be spread out in the x- and y-direction.

The z-axis ($x=y=0$) shows a different behavior, see Figure 3. Here, the x-component $E_x$ and y-component $E_y$ are zero, which can be explained from symmetry. The z-component $E_z$ of the electric field is positive for $z<0$ and negative for $z>0$. This means that electrons from an electron beam will first encounter a decelerating force until $z=0$ is reached. Subsequently, the electron will be accelerated again. Thus, when actuation voltages are applied an electron beam will reach the surface of a device later than when no actuation voltages are applied. Similarly, a time difference can be expected for the secondary electrons detected in SEM imaging. As the energy of primary electrons from the electron beam differs significantly compared to the energy of secondary electrons, this effect will be much stronger for secondary electrons. Therefore, they will be detected later when actuation voltages are applied.

These simulations give clear qualitative insights of the influence of actuation voltages while imaging with electron microscope. The results indicate that the electric fields generated by the actuator should not be ignored.

III - Experimental Details

Preliminary SEM imaging has been performed on slightly different devices than modeled, see Figure 4. These devices and their fabrication have been earlier described in [3]. The geometry differs, but similar electric fields are expected. The device consists of a movable table suspended by four flexible beams. On two opposite sides of the table a comb drive structure is fabricated to actuate the table.

For imaging a FEI Quanta 450 SEM has been used, at a high vacuum of $10^{-3}$–$10^{-5}$ Pa. Acceleration voltages of 5 kV to 25 kV are used, at working distances of 10 to 20 mm. Detection of secondary electrons is done using an Everhart-Thornley Detector at 250 V bias. The SEM chamber has been modified to facilitate electrical connections to actuate the devices using a home-built custom sample holder.

The moving table and substrate of the device are grounded. An AC voltage is applied to the fixed part of the comb drive to actuate the table. The voltage is applied using an Agilent 33120a waveform generator and is amplified ten times using an ESyLAB LM3325 8 channel HV Amplifier with an ESyLAB LM3322 HV Power Supply. For actuation a sine wave is used with typical peak to peak voltages of up to 80 $V_{pp}$. Frequencies were set of 1 to 10 Hz, depending on the chosen scanning speed of the SEM. While actuating the device, the suspended table and several fixed parts are imaged by SEM.
Figure 4: Schematic view of the devices used for measurements. A movable table is suspended by four flexible beams. On the left and right are two comb drive structures, which are fixed to the substrate. The device is actuated by applying a voltage to the left comb drive structure of the device. The imaging area of Figure 5 is indicated also.

IV - Results and Discussion

When imaging fixed parts of the actuated device in the SEM, multiple effects are observed, see Figure 5. The applied voltage results in contrast differences in the SEM image, and a vibration is observed in the image. This vibration is not the result of actuation as the object that is imaged is fixed to the substrate. Therefore, the vibrations must result from an effect on the detected electrons.

The contrast difference is caused by the voltage applied to the object. For instance, when applying a negative voltage to the object, more secondary electrons are detected, which results in a brighter area in the image.

Figure 6 shows the gray level averaged in the x-direction between the red lines, versus the y-direction. The fit in Figure 6 is a fit of the intensity of the detected electrons, based on the inverse distribution function that is shown in Eq. 1.

\[ I(y) = \text{offset} + \frac{\text{scaling}}{\exp\left(k_1 - k_2 V(y)\right)} + 1 \]  

with \( V(y) \) the applied voltage according to Eq. 2:

\[ V(y) = \frac{V_{pp}}{2} \sin\left(b y + \phi\right) \]

In the formulas, \( \text{offset} \) and \( \text{scaling} \) depend on imaging settings, \( k_1 = D_0^0 / D_T \) is the relative detectability, depending on the signal-to-noise ratio and SEM settings. \( D_0^0 \) is the detection level at \( V = 0 \), and \( D_T \) is the detection threshold. \( k_2 = a / D_T \) is the relative sensitivity of the detection to \( V_{pp} \). \( a \) is the detection sensitivity.

Figure 5: SEM image of the fixed part of a comb drive, which is actuated with a 3 Hz 81 V_{pp} sine wave. The scale bar equals 50 μm.

to \( V_{pp} \), with \( V_{pp} \) is the applied peak to peak voltage, \( b \) is the period of the sine in the image, which is calculated from the frequency of the sine wave and the scanning speed of the SEM. \( \phi \) is the phase of the actuation with respect to imaging, which is arbitrary. This model fits the data excellently. The main focus in further research will be on the detection sensitivity \( a \). This parameter is expected to be influenced by several physical phenomena, such as the Fermi level of the electrons in the device and the time-of-flight of the detected secondary electrons.

To further investigate the vibrations in Figure 5, the voltage dependence of the amplitude of the vibrations has been studied. In addition the vibrations have been measured at 3 different locations in the x-direction, with the y-coordinate remaining constant. The first location is shown in Figure 5 and is 0.16 mm away from the comb fingers, the second and third location are 1.3 and 2.3 mm away from the comb fingers, on an electrically grounded part of the device. In these locations, substantial vibrations are observed.

The amplitude of the vibrations has been measured for a range of 0 to 80 V_{pp} in steps of 10 V, at distances of 0.16 mm, 1.3mm and 2.3mm from the place of actuation, see Figure 7. The amplitude has a linear relation with the applied voltage. The measured amplitudes drop with distance from the place where actuation takes place, as is expected.

If we assume that vibrations in the image are accounted only to vibrations in the electron beam that are caused by the applied voltage, our calculations indicate a deflection of less than 100 nm for 5kV acceleration voltage and 100V actuation. This deflection would be significantly lower with a lower actuation voltage, like the maximum peak to peak voltage of 80 V_{pp} that is used in our experiment. Therefore our observations cannot be purely accounted to vibrations in the electron beam.
The vibrations could also be caused by disturbances to the detected secondary electrons. The energy of the primary electrons from the electron beam is equal to several keV’s, depending on the acceleration voltage used. However, secondary electrons have an energy which is in the order of a few or tens eVs. Therefore, the influence of external electric fields on the secondary electrons and their detection is expected to be significantly larger.

The exact mechanism behind this is different from the disturbance of the electron beam that is caused by the applied voltage. The detector detects intensity only, and not the location of the emitted secondary electrons. Vibrations of the secondary electrons are therefore not detected. The location where the detected secondary electrons come from is related to the position of the electron beam and to the detection lag, i.e., the time between the electron beam hitting the object and the time when the emitted secondary electrons from that area are detected. The key to explain why the vibrations that are observed in the SEM images occur, might be in this detection lag. If the electric fields that are caused by the applied voltages cause a deceleration or acceleration of the secondary electrons, the synchronization between the location where the secondary electrons came from and when they were detected might be influenced such that vibrations are observed.

V - Conclusion

We have shown FEM simulations of electric fields in an electrostatically actuated MEMS device. We have calculated the electric field in positions, for instance an aperture, far from the actuator. A quantitative exploration of the influence of the electric fields on incoming electrons has been given. Our analysis shows that an incoming electron beam will be narrowed and decelerated before it arrives at the surface. The next step will be to calculate electron space-time trajectories of electrons from an electron beam.

SEM images of MEMS structures to which an AC voltage is applied show an alternating contrast. This periodic contrast is due to the electrons intensity being influenced by the actuation voltage. We fitted the measured data for the intensity fluctuations to a model which assumes that the intensity variation is caused by modification of the energy barrier for secondary electrons leaving the silicon. Even though the model fits our data very well, the physical nature of the intensity variation is not quite well understood.

SEM measurements of fixed parts on the actuator also show clearly visible vibrations with amplitudes of more than 1 μm up to distances of 2.3 mm from the source of the electric fields. These vibrations cause deformed SEM images. Calculations and qualitative analyses have shown that the vibrations cannot be purely related to deflections of the incident electron beam of the SEM, caused by the applied actuation voltage. A detailed analysis of the causes of the vibration is our main focus to continue this research.

References