Modeling of High-speed Diamond Microswitch

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ABSTRACT

CVD grown diamond is a new attractive MEMS material and has been used here to realize a microswitch with extreme properties. Still at present the technological development requires a fast turnaround of the design based on technological parameters. However FEM simulations are very time consuming, thus a simple model has been developed, allowing fast calculations to predict device performance. Results obtained by the different approaches are given and compared to measured values.

Keywords: Diamond, Microswitch

INTRODUCTION

Owing to its excellent material properties, diamond is an almost ideal material for applications in electronics and micromechanics. Especially due to its superior thermal conductivity diamond is considered for various purposes such as heat sinks or high power transistors. But also the mechanical properties of diamond like the high hardness, fracture strength and Young's modulus make it an interesting alternative to currently used MEMS materials like silicon. Due to the fact that the electrical conductivity of diamond may range from ideal insulating to almost metal-like conducting, fabrication of all-diamond MEMS devices is possible, significantly reducing problems normally found in multi-layer device structures, like thermally induced stress or thermal barriers.

The Chemical Vapor Deposition (CVD) technique allows growth of high quality diamond films with mirror-like surface finish on Si-substrate [1], making it compatible to standard silicon MEMS-technologies and even suitable for monolithic integration with Si circuits.

In this work we investigate the performance of an all-diamond microswitch fabricated using a novel surface micromachining process [2], [3]. The device structure is shown in figure 1, a SEM-picture is given in figure 2. The microswitch is electrostatically actuated by applying a voltage to the gate contact, creating an electric field which bends the free standing cantilever thus closing the signal contact. Though the device structure is quite simple, a description by a single degree of freedom analytical model is only possible for special operation modes [4], since for many cases the bending line of the cantilever is highly nonlinear. This is especially true for high gate voltages or long cantilevers and for the closed state of the contact. Additionally, the material properties of the thin diamond films are quite complex. Since FEM simulations are very time consuming, a one dimensional multi-DOF model based on the equilibrium of forces has been developed to allow a fast analysis of device performance.

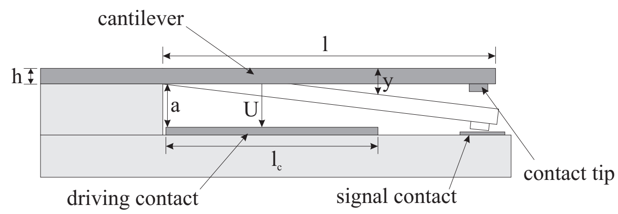

Figure 1: Cross section of diamond microswitch

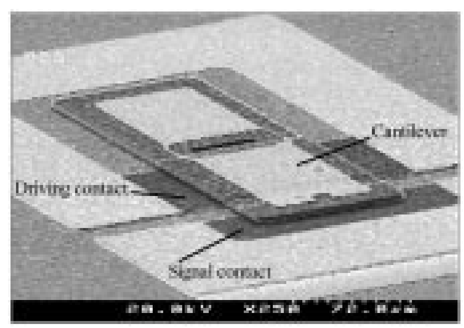

Figure 2: SEM picture of diamond microswitch

Description of the model

The model for the calculation of the dynamic switch characteristics will be described in the following section. It is based on the equilibrium of forces.

A force F acting on a cantilever of thickness h at a distance of x_j from the suspension leads to the following bending line $y(x_i)$

$$y(x_i) = \frac{x_i^2(3x_j - x_i)}{6JE}F \tag{1}$$

where E denotes Young's modulus and $J = \frac{h}{12}$ is the axial moment of inertia. By dividing the cantilever into n elements of equal size Δx, the above expression can be rewritten in matrix form. The distance x_i of the center of element i from the suspension is given by $x_i = \Delta x(i - \frac{1}{2})$. The correlation between the vector $\mathbf{y} = (y_1 \ldots y_n)^T$ denoting the deflection of the cantilever at $x_1 \ldots x_n$ and the force vector $\mathbf{f} = (f_1 \ldots f_n)^T$ denoting the forces acting at $x_1 \ldots x_n$ is then given by

$$\mathbf{y} = \mathbf{S}\,\mathbf{f} \tag{2}$$

where

$$S_{i,j} = \frac{x_i^2(3x_j - x_i)}{6JE} \tag{3}$$

The force vector acting on the cantilever is the sum of the inertia force $\mathbf{f_i}$ and the electrostatic force $\mathbf{f_{el}}$. The inertia force is given by

$$\mathbf{f_i} = \mathbf{M}\,\ddot{\mathbf{y}} = \begin{pmatrix} m_1 & & \\ & \ddots & \\ & & m_n \end{pmatrix} \ddot{\mathbf{y}} \tag{4}$$

m_i denotes the mass of element i.

The electrostatic force $\mathbf{f_{el}} = (f_{el,1} \ldots f_{el,n})^T$ acting on element i can be calculated using the approximation of a capacitor with two parallel plates of distance $a - y_i$, where a is the height of the air gap between the cantilever and the ground contact. Given the energy stored in the electric field of a capacitor $W_{el} = \frac{1}{2}CU^2$ with $C = \varepsilon\frac{A}{d}$, the electrostatic force can be obtained by calculating dW_{el}/dy:

$$f_{el,i} = \frac{\varepsilon U^2 l_i}{2(a - y_i)^2} \tag{5}$$

where l_i is the length of element i. Since the length of the driving contact l_c is less than the total length of the cantilever l (see figure 1), $f_{el,i} = 0$ for $x_i > l_c$.

Using the equilibrium of forces, the following differential equation describing the dynamic behaviour of the switch can be obtained:

$$\mathbf{y} = \mathbf{S}(\mathbf{f_{el}} - \mathbf{M}\ddot{\mathbf{y}}) \quad \text{or} \quad \ddot{\mathbf{y}} = -\mathbf{M^{-1}S^{-1}y} + \mathbf{M^{-1}f_{el}} \tag{6}$$

In case of elements of similar size and therefore mass, the mass matrix $\mathbf{M}$ becomes a scalar value m_i. The second order differential equation can be rewritten as a differential equation of first order to allow a numeric solution of the highly nonlinear equation:

$$\begin{pmatrix} \mathbf{y} \\ \dot{\mathbf{y}} \end{pmatrix}' = \begin{pmatrix} 0 & \mathbf{E} \\ -\frac{1}{m_i}\mathbf{S^{-1}} & 0 \end{pmatrix} \begin{pmatrix} \mathbf{y} \\ \dot{\mathbf{y}} \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{m_i}\mathbf{f_{el}} \end{pmatrix} \tag{7}$$

where $\mathbf{E}$ is the unity matrix.

This nonlinear equation can be solved numerically by assuming the electrostatic force vector to be constant over one time step interval dt and recalculating the value of $\mathbf{f_{el}}$ after each time step.

Since the eigenvalues λ_i of the matrix

$$\begin{pmatrix} 0 & \mathbf{E} \\ -\frac{1}{m_i}\mathbf{S^{-1}} & 0 \end{pmatrix} \tag{8}$$

are all imaginary, explicit algorithms of low order (like Euler's method) cannot be used to solve equation (7), because they are unstable. Therefore either implicit methods or higher order methods have to be employed. We have used the classical Runge-Kutta-method of forth order, which is stable for a time step size dt which satisfies $dt < \frac{2\sqrt{2}}{\max(|\lambda_i|)}$.

Since diamond films and free standing diamond structures usually show a significant amount of intrinsic stress leading to a bending of the cantilevers (see figure 3), stress effects also have to be included in the calculations. Since stress states, which are constant over the thickness of the cantilever only lead to a small expansion of the cantilevers and therefore hardly influence the device performance, only inhomogeneous stress components have to be taken into account. Assuming a linear stress distribution over the thickness of the cantilever, σ can be written $\sigma_x(y) = \frac{\Delta\sigma}{h}y$ for $-h/2 < y < h/2$. The resulting strain thus becomes $\varepsilon_x(y) = \frac{\Delta\sigma}{Eh}y$. This strain leads to a bending of the cantilever. Assuming only small strains, the resulting bending radius can be calculated to be

$$R = \frac{h}{\Delta\varepsilon} = \frac{hE}{\Delta\sigma} \tag{9}$$

On the other hand, the bending radius can be written as

$$R = \left(\frac{d^2y(x)}{dy^2}\right)^{-1} \tag{10}$$

Using the discretisation in elements of equal sizes Δx described above, a strain vector describing the strain $\sigma_{x,i}$ at element i can be written as follows

$$\Delta\sigma_i = \frac{Eh}{(\Delta x)^2}(2y_i - y_{i-1} - y_{i+1}) \tag{11}$$

which can also be written in matrix form

$$\boldsymbol{\sigma} = \mathbf{B}\,\mathbf{y} \tag{12}$$

Using equations (2) and (12) an equivalent force vector describing the influence of the intrinsic stress can be calculated as follows

$$\mathbf{f_{str}} = \mathbf{S^{-1}B^{-1}}\boldsymbol{\sigma} \tag{13}$$

This force vector can than be included in the model by adding it to equation (7).

Contact between the cantilever and the ground plate can be accounted for by setting y_i to a value of a for the

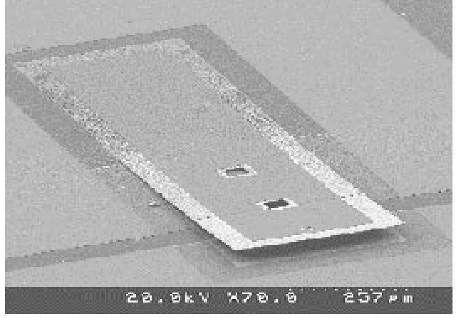

Figure 3: Bending of free standing diamond cantilever

next time step when contact is reached. An equivalent counteracting force is then calculated to hold the cantilever in its position for this time step. Due to the high hardness of diamond, sticking of the diamond-diamond contacts can be neglected for the calculations.

Damping effects are currently not included in the model. Resonance measurements of oscillating free standing cantilevers show a very high Q, therefore the main damping mechanism is believed to be the gas damping due to the displacement of air underneath the cantilever.

Modeling parameters

The parameters used for the modeling of the diamond microswitch are shown below. Since the material properties of CVD grown diamond vary significantly with the deposition process, data found in the literature can hardly be used. Therefore, measured data was used in the simulation. The effective stress $\boldsymbol{\Delta\sigma}$ was extracted by measuring the bending line $\mathbf{y}$ of the cantilever and calculating the vector $\boldsymbol{\sigma}$ using equation (12). The following material parameters were used in the simulation:

E_Y	800 GPa
ρ_d	3.5 g/cm^3
ρ_{Au}	19.3 g/cm^3
ε	$8.854 \cdot 10^{-12}$ As/Vm
h	3 μm
w	400 μm
l	1100 μm
l_c	750 μm
a	2.3 μm

The influence of the metallization on top of the cantilever (mainly Gold) on the stiffness is small due to the low Young's modulus of Gold (78 GPa) and the small thickness (0.5 μm). Since the density of Gold (19.3 g/cm^3) is significantly higher than of Diamond (3.5 g/cm^3), the influence on the mass of the cantilever was taken into account.

FEM simulations

The FEM simulations were carried out using the standard ANSYS software package. The coupling between the electrostatic and mechanical behaviour was simulated by first calculating the electrostatic forces resulting from the electric field distribution in the respective structure and then simulating the deflection resulting from these forces. This calculation was repeated for each time step. Since for this procedure it is assumed, that the deformation during one time step is small and thus does not effect the electric field distribution for the time step, the step size must be chosen accordingly. Stress effects were included by defining an appropriate position dependent thermal expansion of the cantilever material to reproduce the measured bending line.

Results

The switch-on characteristics of the device have been calculated using the model and 3d FEM simulations. A comparison between the two different approaches is given in figure 4. It shows the calculated switch-on characteristics, namely the time dependent deflection at the cantilever tip, for a gate voltage of 7 V. A good agreement between the calculations can be observed, though three dimensional effects are not included in the model. The model, which includes contact effects also reveals a chattering of the contact.

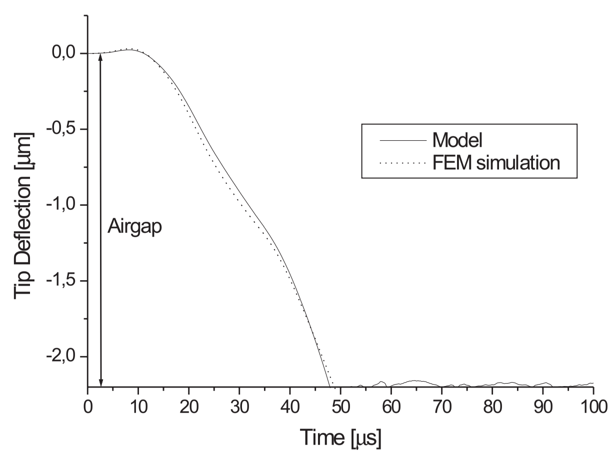

Figure 4: Switch-on characteristics of a 1100 μm long cantilever at 7 V gate voltage

Figure 5 shows the gate voltage dependence of the switch-on time calculated using the two different approaches. Again, a good agreement is found.

The switch-off characteristic is especially important, since the energy stored in the deflected cantilever for a closed switch may lead to a repeated contact after opening the switch, as shown in figure 4. This may be

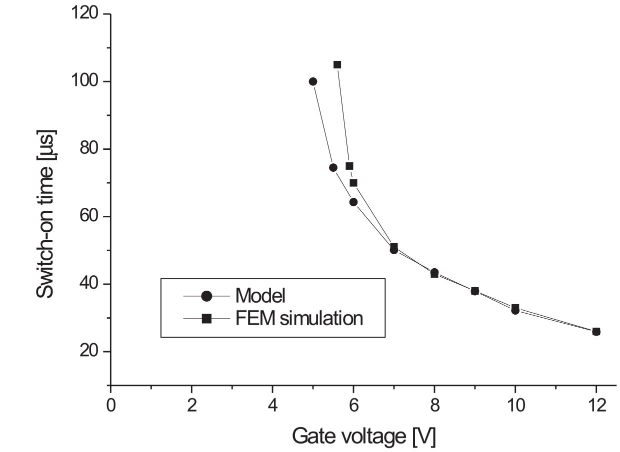

Figure 5: Gate voltage dependence of the switch-on time

avoided using an appropriate gate voltage pulse to slow down the upward motion of the cantilever. This voltage pulse may be obtained using the calculations described above. The results of the calculation are also shown in figure 6. It can be seen, that in the device structure discussed the repeated contact of the cantilever may be avoided by a 11 V gate voltage pulse starting 10 μs after opening the contact.

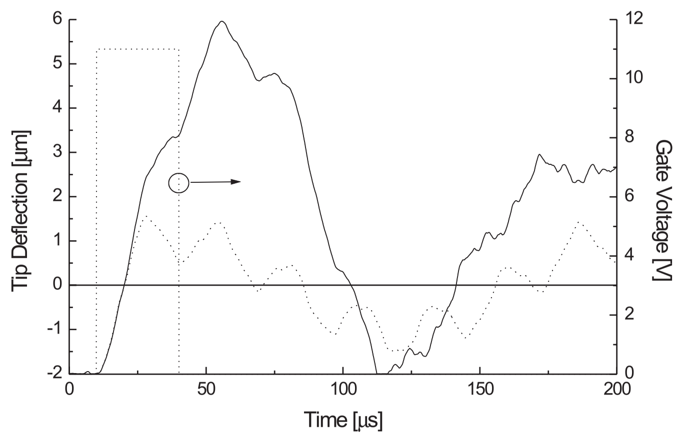

Figure 6: Switch-off characteristics of a 1100 μm long cantilever with (dashed) and without (solid) slow down pulse after contact opening

As a last example, the switch-on characteristics of a pre-stressed device have been investigated. The results are shown in figure 7. Again, a quite good agreement with FEM simulations is found. The FEM approach predicts slightly higher switching times and threshold voltage, because three dimensional effects become more important in this case, especially the stiffening of the cantilever due to a transverse bending. Measured results are also shown in figure 7, showing a significant deviation. Though the threshold voltage of the device can be predicted quite satisfactory, measured switching times are clearly higher.

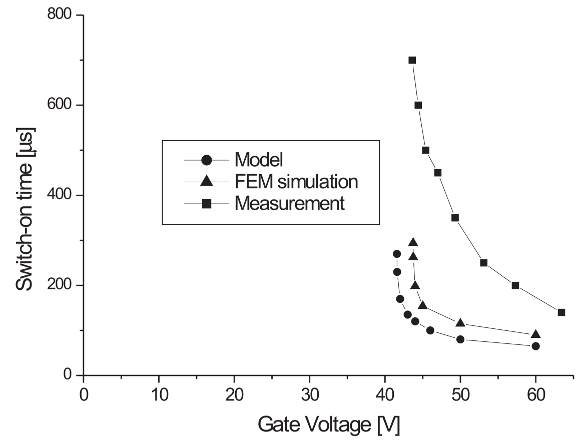

Figure 7: Switch-on time of prestressed cantilever

SUMMARY

The model developed for a fast simulation of diamond microswitches showed a good agreement with results obtained by FEM and can therefore be used to replace time consuming FEM simulations. Stress effects are often observed in diamond devices and have also been included in the model. Though showing a good agreement with FEM simulations including stress effects and also predicting the threshold voltage of the devices quite accurate, agreement with measured switching times is not satisfactory. Therefore more sophisticated models for the quite complex material parameters of diamond devices still have to be developed.

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