Influence of Surface Force on Motion of An Electrostatic Microstructure

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In an electrostatic microstructure with a movable electrode supported by a cantilever beam and counter electrodes, voltage dependency of displacement of the movable electrode is studied by taking surface force into consideration. The displacement change is analyzed theoretically with the energy model which determines the stable displacement state of the movable electrode from the minimum energy state of the total energy of elastic energy, electrostatic energy and adhesion energy between two surfaces. The relation between the surface force at contact parts of the movable electrode with the counter one and a hysteresis voltage of capacitance (between the both electrodes)-voltage characteristics (C-V characteristics) was investigated and a magnitude range of the surface force in which stiction of the movable electrode occurs is derived. In an experiment which simulated electrical contacts of the electrostatic microstructure with charged objects, the surface force increased with increase of the charge amount of the object. In measurements of C-V characteristics in positive and negative voltage regions, the C-V characteristics shifted to the positive voltage region and the shift was larger in a device with larger surface oxide layer of the movable electrode. This voltage shift is thought to be caused by a positive electrical charge remaining in the oxide layer.

Keywords: Microstructure, Electrostatic force, Surface force, Energy model, Electrification, Oxide charges

1. INTRODUCTION

In electrostatic microstructures such as micro scanners, micro relays and servo accelerometers, mechanical response of a movable electrode to an electrostatic applied force is essential for their operation. Application of the electrostatic force to the movable electrode is also carried out in self-diagnoses of the electrostatic microstructures when they are used in systems which demand high reliabilities [1]. The electrostatic force can be easily applied to the movable electrode only by forming a counter fixed electrode, and the magnitude of the force is easily changed by changing the voltage between the both electrodes. Therefore, in these devices, it is important to know precisely the behavior of the movable electrode under the application of the electrostatic force between the both electrodes.

On the other hand, surface forces between two counter surfaces have also large influences on the operations of the microstructures [2-6].

In this paper, we have investigated a mechanical response of a movable electrode of an electrostatic microstructure under the electrostatic force applied between the movable and the fixed electrodes. Effects of the surface force to the response characteristics are taken into consideration. Voltage dependencies of the motion of the

Figure 1: Structure of the electrostatic microstructure studied

movable electrode is analyzed theoretically with the energy model. Some experimental results of the response characteristics, which show the effects of the surface force, are described.

2. THEORETICAL ANALYSIS OF CAPACITANCE -VOLTAGE CHARACTERISTICS

Figure 1 shows a cross section of the electrostatic microstructure studied. It has a silicon movable electrode, a silicon cantilever beam to support the movable electrode and counter fixed electrodes formed by a thin metal film (Mo). To avoid a direct electrical contact of the movable electrode with the fixed one, small stoppers P_1 , P_2 , Q_1 and

Table 1: Various dimensions of the electrostatic microstructure

Cantilever	Length (L_1)	800
	Width (W_1)	250
	Thickness (T_1)	16
Movable electrode	Length (L_2)	1300
	Width (W_2)	1800
	Thickness (T_2)	210
Stopper	Height (H)	0.8
Gap width (D_0)		3.0

(Unit: μm)

Q_2 of an insulator (SiO_2) were formed at four corners of each counter surface of the movable electrode. Table 1 shows device dimensions used in the calculation.

When the deformation of the movable electrode and the twist of the cantilever beam are small, the displacement state of the movable electrode is determined by the displacement Y_p of the stoppers P_1 and P_2 and the displacement Y_q of the stoppers Q_1 and Q_2 . The behavior of the movable electrode for an applied voltage between the both electrodes is determined by the total energy of elastic energy U_m stored in the cantilever beam, electrostatic energy U_e of an electric field between the electrodes and adhesion energy U_{ad} between the stoppers and the fixed electrode when they contact each other.

The elastic energy U_m is calculated by the next equation [7].

$$U_m = (1/2) \int_0^{L_1} (M^2/EI) dx \quad (1)$$

Where E is the Young's modulus of the cantilever beam material (single crystal silicon), I is the moment of inertia of the beam section and L_1 is the length of the cantilever beam. M is the bending moment at the x -section (the sign is positive when the upper layer of the beam is compressed). The bending moment M is determined uniquely for a given displacement state (Y_p, Y_q) and expressed as follows.

$$M = Ax + B \quad (2)$$

Where A and B are given by the next equations.

$$A = \left(\frac{6EI}{L_1^2} \right) \left(\frac{Y_q - Y_p}{L_2} - \frac{2Y_p}{L_1} \right) \quad (3)$$

$$B = - \left(\frac{2EI}{L_1} \right) \left(\frac{Y_q - Y_p}{L_2} - \frac{3Y_p}{L_1} \right) \quad (4)$$

Where L_2 is the length of the movable electrode. By substituting eq.(2) into eq.(1), the elastic energy U_m is expressed by the displacements Y_p and Y_q through the parameters A and B , as shown in eq.(5).

$$U_m = (1/6EI) (A^2 L_1^2 - 3ABL_1 + 3B^2) L_1 \quad (5)$$

Figure 2: Total energies in various displacement states of the movable electrode at $V=1V$

Figure 3: Total energies in various displacement states of the movable electrode at $V=5V$

On the other hand, the electrostatic energy U_e is given by eq.(6).

$$U_e = - (1/2) CV^2 \quad (6)$$

Where C is a capacitance between the both electrodes and expressed as follows also by using the displacements Y_p and Y_q .

$$C = \frac{\epsilon_0 S}{Y_q - Y_p} \log \left(\frac{D_0 - Y_p}{D_0 - Y_q} \right) \quad (7)$$

Where S is the counter surface area of the both electrodes, D_0 is the gap width between them when the displacement of the movable electrode is zero and ϵ_0 is the dielectric constant of vacuum.

As the effect of the attractive surface force, the following adhesion energy U_{ad} was added to the sum of the elastic energy U_m and the electrostatic energy U_e only in the deformation states in which the movable electrode contacted with the fixed one through the stoppers.

$$U_{ad} = -F_{ad} Y_{ad} \quad (8)$$

Figure 4: Voltage dependence of the displacements Y_p and Y_q

Where Y_{ad} is the force range of the surface force F_{ad} and was given by the next equation.

$$Y_{ad} = (D_0 - H) / N \quad (9)$$

Where H is the height of the stoppers and N is the number of discrete values of the displacement Y_p or Y_q in the numerical calculation.

Figures 2 and 3 show dependencies of the total energy $U_{tot} = U_m + U_e$ on the displacement state (Y_p, Y_q) of the movable electrode when the surface force is zero and the applied voltages are 1V and 5V, respectively. The stable displacement state of the movable electrode in each voltage is given by the displacement state (Y_p, Y_q) in which the total energy U_{tot} is minimum. The minimum energy state is $(Y_p, Y_q) = (0.04\mu\text{m}, 0.18\mu\text{m})$ at $V=1\text{V}$ and $(Y_p, Y_q) = (0.66\mu\text{m}, 2.20\mu\text{m})$ at $V=5\text{V}$.

Figure 4 shows calculated changes of the displacements Y_p and Y_q in the stable displacement states when the voltage is increased from 0 to 15V and decreased from 15V to 0. In the calculation, the surface force which acts in the contact parts of the stoppers and the fixed electrode, is supposed to be zero. The stable displacement states were calculated by the voltage step of 0.3V.

In the voltage increase process, the displacements Y_p and Y_q increase suddenly near $V=2.1\text{V}$ (the first pull-in voltage: V_{P11}) and reach $0.57\mu\text{m}$ and $2.20\mu\text{m}$, respectively. This means that only the stoppers Q_1 and Q_2 which are formed near the tip of the movable electrode contact with the fixed electrode at this voltage. In the voltage larger than 2.1V, the displacement Y_q is constant to 15V. On the other hand, the displacement Y_p increases gradually to 10.2V and raises up to $2.20\mu\text{m}$ at 10.5V (the second pull-in voltage: V_{P12}). At this voltage, all the stoppers contact with the fixed electrode.

In the voltage decrease process, the displacement Y_p falls down at 9.0V and 1.5V and the displacement Y_q at

Figure 5: Voltage dependence of the capacitance between the movable and the fixed electrodes

Figure 6: Surface force (per one stopper) dependence of hysteresis voltage $V_{P11} - V_{R1}$

1.5V. That is to say, the stoppers P_1 and P_2 separate from the fixed electrode first at 9.0V (the second release voltage: V_{R2}) and then the stoppers Q_1 and Q_2 separate at 1.5V (the first release voltage: V_{R1}).

Figure 5 shows the capacitance change of the stable displacement state calculated by eq.(7) from the displacement changes in Fig. 4. The capacitance change in the voltage increase process and that in the voltage decrease process are different, i.e. there exists a hysteresis. We call the difference between the pull-in voltage and the corresponding release voltage as a hysteresis voltage.

The hysteresis voltage is influenced by the surface force between the stoppers and the fixed electrode. Figure 6 shows the surface force dependence of the hysteresis voltage ($V_{P11} - V_{R1}$). The horizontal axis indicates the surface force per one stopper. The hysteresis voltage increases nonlinearly with the increase of the surface force. When

Figure 7: Measurement circuit of the capacitance change

Figure 8: Examples of measured capacitance-voltage characteristics

the surface force is larger than $4.7\mu\text{N}$, the hysteresis voltage becomes larger than the magnitude of the first pull-in voltage 2.1V . This means that the movable electrode does not return to the original position when the voltage is reduced to zero, i.e. a stiction between the movable electrode and the fixed one arises.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Voltage dependencies of the capacitance between the movable and the fixed electrodes of sample devices were measured by a circuit shown in Figure. 7. LCR meter was used in a measurement condition of 100kHz and 50mV (effective voltage), and DC bias voltage which was changed by a step of 0.1V or 0.2V was added to the measurement AC voltage. The silicon part of the device was connected to the ground potential level and a positive or a negative voltage was applied to one of the fixed electrodes. The other fixed electrode was also connected to the ground level to avoid an application of the electrostatic force between this electrode and the movable one. The gravitational force perpendicular to the movable electrode was zero.

Figure 8 shows examples of measured capacitance-voltage characteristics (C-V characteristics). The applied voltage was increased from 0V to $+10\text{V}$ and then was decreased from $+10\text{V}$ to 0V . There existed the hysteresis in

Figure 9: Circuit for simulating contact of the electrostatic microstructure with charged body

the characteristics of the samples A and B. The capacitance of the sample B didn't return to the original value when the voltage was decreased to zero. As described in the above, this is thought to be caused by the stiction of the movable electrode to the fixed one due to the surface force between the stoppers Q_1 and Q_2 and the fixed electrode. The total surface force was estimated at about $6\mu\text{N}$ in the sample A and larger than $9.5\mu\text{N}$ in the sample B from the relation of Fig. 4.

It is known that the surface force in the microstructures is influenced by many kinds of factors such as humidity, degree of hydrophilicity of the surface, heat treatment and electrification of an intermediate insulation layer between the movable and the fixed electrodes [4-5]. In the next, we will describe influences of the surface force especially related to electrical properties of the surface insulation layer of the movable electrode on the C-V characteristics.

After fabrications, the static electricity can be easily stored in the usual electrostatic microstructures by contacts of their electrode terminals with charged objects. This contact of the electrostatic microstructure with charged bodies was simulated by a circuit shown in Fig. 9. At first, the capacitance (200pF) was charged by connecting it with a DC voltage source and then the electrode of the device was connected with the charged capacitance by changing a switch circuit. After the electrical charge stored in the device electrodes was discharged, C-V characteristics of the device were measured by the circuit of Fig. 7.

Figure 10 shows changes of the C-V characteristic of a sample device when the charge voltage of the capacitance was changed. It is seen that the hysteresis voltage of the C-V curve increases with increase of the charge voltage, i.e. the amount of the electrical charge stored in the condenser. In these case, the surface forces were estimated at $6.0\mu\text{N}$, $8.4\mu\text{N}$ and larger than $9.5\mu\text{N}$ for the charge voltages of 0V , 20V and 40V , respectively.

The increase of the surface force after the contact with the charged body is thought to come from an accumulation of an electrical charge in the surface SiO_2 layer (stopper) or

Figure 10: Change of C-V characteristics of a sample device when charge voltage of the condenser was changed

a residual polarization of SiO_2 layer due to the application of the large electric field to this layer [5].

Figure 11 shows the C-V curves of two types of devices with different shapes of surface SiO_2 layers. Fig. 11(a) shows the characteristic of the device shown in Fig. 1, i.e. SiO_2 layer ($150\mu\text{m} \times 150\mu\text{m}$) was formed at the four corners of the upper and lower surfaces of the movable electrode (Sample C). The ratio of the surface oxide area to the total (upper and lower) surface area of the movable electrode was less than 4%. On the other hand, Fig. 11(b) shows the characteristic of the device in which whole of the upper and lower surfaces was covered by SiO_2 layer (Sample D). The applied voltage was changed from 0V to +3V and decreased to -3V and then increased to 0V.

The electrostatic force F_{es} between two parallel plate electrodes separated by a distance d is given by $F_{es} = \epsilon_0 S V^2 / 2d^2$ and proportional to square of the applied voltage V . This means that the capacitance change between the movable and the fixed electrode is expected to be independent of the polarity of the applied voltage. However, it is observed that the C-V characteristics in Fig. 11 doesn't have symmetry with respect to the axis of $V=0$. The asymmetry of the characteristics seems to come from a shift of a symmetry axis to the positive voltage region. From comparison of the pull-in voltages of

Figure 11: C-V characteristics of two kinds of samples:
(a) SiO_2 layer (stopper) is formed at four corner of the upper or lower surface of the movable electrode,
(b) whole of the main surfaces of the movable electrode are covered by SiO_2 layer

the positive and the negative voltage regions, the shift of the symmetry axis is estimated at 0.1V in Fig. 11(a) and from 0.7V to 0.8V in Fig. 11(b).

In Fig. 11(b), when the voltage was returned to zero just after the application of the minus voltage, the capacitance didn't return to the original value (13.8pF). This means that the stiction between the movable and the fixed electrodes arose similar to the sample B of Fig. 8.

One of the possible reasons to cause such a voltage shift (especially in Fig. 11(a)) is an additional bias voltage added to the measurement DC voltage. When two different conductive materials contact each other, a voltage difference (contact potential difference) appears between them. Even if such conductive materials are connected electrically through other conductive materials, the voltage difference of the same magnitude is also generated. In case of the present device, it is thought that the voltage difference which was equal to the contact potential difference of the materials of the movable and the fixed electrodes (Si and Mo) appeared between the both electrodes and such a voltage was added to the measurement DC voltage.

On the other hand, the voltage shift was larger in the

sample having the larger oxide layer (Sample D). This means that the SiO₂ layer was related to the shift. As described in the appendix, when a positive charge of an appropriate density ($\sim 2 \times 10^{10}/\text{cm}^2$) is assumed in the oxide layer, the shift of the C-V curve to the positive voltage region and the stiction in Fig. 11(b) can be explained as the effects of this charge.

One of origins of this positive charge is the contact electrification due to the contact of the oxide layer with the fixed electrode. However, the influence of the contact electrification on the C-V characteristics and the surface force is thought to be small since the real contact area was much smaller than the observed contact area and the total amount of the generated charge was very little [5].

On the other hand, in the field of semiconductor devices, it is known that various kinds of electrical charges such as mobile ions (Na⁺, K⁺) and trapped charges exist in the oxidized silicon layer and these charge densities depend on the fabrication process of the device [8]. In Si-SiO₂ MOS (Metal-Oxide-Semiconductor) devices of the early period (1960's), electrical charge densities in the region of $10^{12} \sim 10^{13}/\text{cm}^2$ were observed in the SiO₂ layer by measurements of C-V characteristics of MOS diodes. These charge densities are much larger than the density of electrons ($1.8 \times 10^{10}/\text{cm}^2$) induced on counter surfaces of a parallel plate condenser when its gap width ($D_0=3.0\mu\text{m}$) is the same as that of the present microstructure and the applied voltage is 10V.

In the electrostatic microstructures, insulation materials including SiO₂ are often used to avoid direct electrical contacts of the movable electrode with the fixed one. Therefore, it is necessary to study electro-mechanical effects of the insulation layer on the electrostatic microstructure more precisely.

4. CONCLUSIONS

Influences of surface force on a motion of an electrostatic microstructure, which has a movable electrode supported by a cantilever beam and counter fixed electrodes, was studied theoretically and experimentally.

Voltage dependency of the displacement of the movable electrode was analyzed with the energy model which determined the stable displacement state of the movable electrode from the minimum energy state of the total energy of elastic energy, electrostatic energy and adhesion energy between contact surfaces. A hysteresis voltage defined as a difference between a pull-in voltage and a corresponding release voltage increased nonlinearly with increase of surface force in contact parts of the both electrodes. Magnitude range of the surface force in which stiction of the movable electrode occurred was derived.

From an experiment which simulated electrical contacts

of the device with charged objects, it was seen that the surface force increased with increase of the charge amount of the object.

In measurements of C-V characteristics in positive and negative voltage regions, it was observed that the C-V characteristics shifted to the positive voltage region and the shift was larger in a device with larger surface oxide layer of the movable electrode. It is thought that this voltage shift was caused by a positive electrical charge remaining in the oxide layer.

APPENDIX

Effects of an electrical charge in a surface oxide layer on an electrostatic microstructure has been evaluated by a simple theoretical analysis. Figure A-1 shows a model for the study. A surface of a movable electrode is covered by a SiO₂ layer (thickness: t). To simplify the consideration, we assume a plane charge (density: σ) as the oxide charge. In Fig. A-1, x is the distance between the plane charge and the Si/SiO₂ interface. A small voltage V (in which a bending of energy band of Si is enough small near Si/SiO₂ interface) is applied between the movable electrode and a fixed one. Since electric fields inside of the both electrodes are zero, the next relation can be obtained.

$$\sigma_1/2\epsilon_0 + \sigma_2/2\epsilon_0 + \sigma/2\epsilon_0 = 0 \quad (\text{A1})$$

Where σ_1 and σ_2 are densities of electrical charges induced on the surfaces of the movable electrode and the fixed one, respectively. Electric field E_1 between the Si/SiO₂ interface and the oxide charge σ , electric field E_2 between the oxide charge σ and the SiO₂ surface and electric field E_3 in the space between the SiO₂ layer and the fixed electrode are given by the next equations.

$$E_1 = (-\sigma_1 + \sigma_2 + \sigma)/2\epsilon_0\epsilon_r \quad (\text{A2})$$

$$E_2 = (-\sigma_1 + \sigma_2 - \sigma)/2\epsilon_0\epsilon_r \quad (\text{A3})$$

$$E_3 = (-\sigma_1 + \sigma_2 - \sigma)/2\epsilon_0 \quad (\text{A4})$$

Where ϵ_r is the relative dielectric constant of SiO₂ ($\epsilon_r=3.9$). When a voltage difference between the both electrodes is V , the relation (A5) is obtained.

Figure A-1: Model for analyzing effects of the oxide charge on the electrostatic microstructure

$$E_1x + E_2(t-x) + E_3(d-t) = V \quad (A5)$$

By simultaneously solving eq.(A1) and the equation obtained by substituting eqs.(A2), (A3) and (A4) into eq.(A5), the next surface charge σ_2 is obtained.

$$\sigma_2 = \frac{x\sigma - \epsilon_0\epsilon_r V}{(\epsilon_r - 1)t - \epsilon_r d} \quad (A6)$$

The electrostatic force F_{es} between the movable and the fixed electrodes is given by the next equation.

$$\begin{aligned} F_{es} &= (\sigma_1 + \sigma)\sigma_2 / 2\epsilon_0 \\ &= -\sigma_2^2 / 2\epsilon_0 \\ &= -\frac{S}{2\epsilon_0} \left\{ \frac{x\sigma - \epsilon_0\epsilon_r V}{(\epsilon_r - 1)t - \epsilon_r d} \right\}^2 \end{aligned} \quad (A7)$$

From eq.(A7), the voltage V_0 in which the electrostatic force F_{es} becomes zero is calculated as follows.

$$V_0 = x\sigma / \epsilon_0\epsilon_r \quad (A8)$$

V - F_{es} curve given by eq.(A7) is symmetry with respect to the axis of $V=V_0$. Therefore, the voltage V_0 becomes the voltage shift of C-V curve due to the oxide charge when contact potential difference of the electrode materials is zero.

When the oxide layer contacts with the fixed electrode ($d=t$) in $V=0$, the electrostatic force F_{es} of eq.(A7), i.e. the stiction force, becomes as follows.

$$F_{es} = -\frac{S}{2\epsilon_0} \left(\frac{x}{t} \right)^2 \sigma^2 \quad (A9)$$

For example, when the oxide charge of the density of $\sigma = 3.2 \times 10^{-5} \text{ C/m}^2$ ($2.0 \times 10^{10} \text{ /cm}^2$) is distributed near the surface of SiO_2 layer of thickness of $0.8\mu\text{m}$ ($x = 0.8\mu\text{m}$), the voltage shift V_0 of the C-V characteristic is estimated at 0.74V from eq. (A8). Further, the stiction force (surface force) due to this oxide charge between a SiO_2 stopper of the size of $150\mu\text{m} \times 150\mu\text{m}$ and the fixed electrode is calculated at $1.3\mu\text{N}$ from eq. (A9).

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