ELECTROSTATIC SILICON WAFER SUSPENSION

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ABSTRACT

This paper describes an experimental electrostatic silicon wafer suspension system, which is a part of preliminary research towards the development of contactless wafer manipulators for use in Ultra-High-Vacuum (UHV) and ultra clean environments. A silicon wafer with 4 inch diameter has been suspended successfully without any mechanical contact by actively controlling the electrostatic attractive force acting on it.

INTRODUCTION

Electrostatic suspension is a technique to levitate an object by controlling an attractive force on it. Compared to magnetic suspension, electrostatic suspension has not been studied extensively, since there are difficulties associated with the high voltage levels required to achieve suspension. Early research on electrostatic suspension was in relation to "electric vacuum gyros", which were used as an inertial reference in the navigation system for Polaris submarines [3]. In recent years, this technique seems to have made a revival due to the following two main reasons: (1) Its usefulness in the elimination of friction and physical contact in microactuators and micromotors has been widely recognized. Electrostatic suspension for microbearings have been experimentally studied [4]. (2) Its advantages over magnetic suspension are becoming more and more apparent. While magnetic suspension can only suspend ferromagnetic materials, electrostatic suspension can suspend a variety of materials such as metal, semiconductors, and dielectrics. It follows that, in this paper, we describe an experimental electrostatic silicon wafer suspension system which is a part of preliminary research towards the development of contact-less wafer manipulators for use in Ultra-High-Vacuum (UHV) and ultra clean environments, both of which are necessary for manufacture of the new generation semiconductor devices.

LIST OF SYMBOLS

The symbols used in this paper are listed in Table 1, where i = 1, 2, 3, 4. The superscript "~" denotes total value, and the subscript "e" denotes values at the equilibrium state.

MODEL OF SUSPENSION SYSTEM

General Equation of Motion

Fig. 1 is a schematic representation of the experimental system which defines the coordinate system to be used in our analysis.

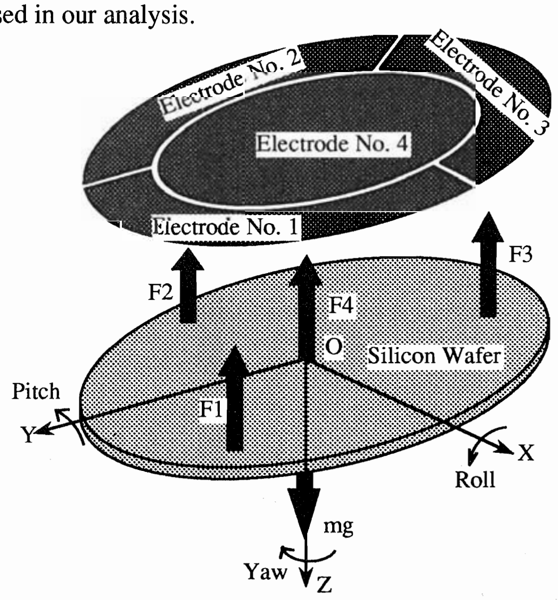

FIGURE 1 Coordinate System and Force Distribution

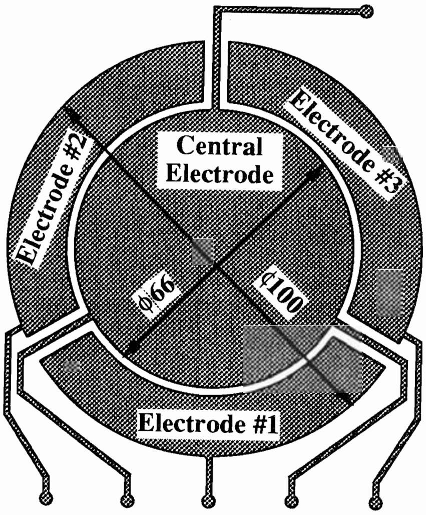

FIGURE 2 Electrode Pattern

Four electrodes are mounted in planar array, as shown in Fig. 2. The movement of the wafer can be controlled in three degrees of freedom: one associated with the translational motion in vertical direction, the other two with the rotational motion, roll and pitch. Generally, they are described by three second-order nonlinear differential equations. However, in a real suspension system, the following two assumptions are usually reasonable: (1) The roll and pitch angles are very small so that $\cos\theta_x$, $\cos\theta_y \approx 1$ and $\sin\theta_x$, $\sin\theta_y \approx 0$, and (2) The product of velocities and angular velocities are small and can be ignored. With these simplifications, the equations of motion of the wafer can be written as

$$\begin{bmatrix} \ddot{Z}c \\ \ddot{\theta}x \\ \ddot{\theta}y \end{bmatrix} = Cm \times \begin{bmatrix} Fz \\ Mx \\ My \end{bmatrix} \tag{1}$$

where

$$Cm = \begin{bmatrix} 1/m & 0 & 0 \\ 0 & 1/Ix & 0 \\ 0 & 0 & 1/Iy \end{bmatrix}$$

$$Ix = Iy = mR_w^2/4$$

The position and orientation of the wafer can be calculated from the outputs of three gap sensors. In the experimental system, the sensor positions sit at the corners of an equilateral triangle which can be circumscribed by a circle of radius R_s .

TABLE 1 List of Symbols

ε	Permittivity of air	farad/m
s	Area of each of outer electrode	m^2
m	Mass of wafer	kg
R_s	Distance of sensors from origin of coordinate system	m
R_f	Distance of center of force from origin of coordinate system	m
R_w	Radius of wafer	m
I_x	Inertial momentum about x axis	$kg \cdot m^2$
I_y	Inertial momentum about y axis	$kg \cdot m^2$
z_i	Gap between electrode No. i and wafer	m
C_i	Capacitance between electrode No. i and wafer	farad
F_i	Electrostatic force generated by electrode No. i	N
Z_c	Displacement of center of wafer	m
θ_x	Roll angle	rad
θ_y	Pitch angle	rad
F_z	Force in vertical direction	N
M_x	Torque about x axis	$N \cdot m$
M_y	Torque about y axis	$N \cdot m$
V_i	Voltage applied on electrode No. i	V
Z_e	Equilibrium gap	m
V_e	Bias voltage applied to each of outer electrodes	V
F_e	Electrostatic force at equilibrium state	N
K_i	Proportional coefficient of controller No. i	V/m
D_i	Derivative coefficient of controller No. i	$V \cdot s/m$

$$\begin{bmatrix} Zc \\ \theta x \\ \theta y \end{bmatrix} = Cs \times \begin{bmatrix} \tilde{z}1 \\ \tilde{z}2 \\ \tilde{z}3 \end{bmatrix} \tag{2}$$

where

$$Cs = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ -2/(3Rs) & 1/(3Rs) & 1/(3Rs) \\ 0 & -1/(\sqrt{3}Rs) & 1/(\sqrt{3}Rs) \end{bmatrix}$$

The total force and the torques can be obtained from the forces generated by four electrodes. Each of the distributed field forces generated by four electrodes can be treated as an equivalent concentrated force with its point of application at the center of the electrode. Centers of the three outer electrodes sit at the corners of an equilateral triangle which can be circumscribed by a circle of radius R_f.

$$\begin{bmatrix} F_c \\ M_x \\ M_y \end{bmatrix} = C_f \times \begin{bmatrix} \tilde{F}_1 \\ \tilde{F}_2 \\ \tilde{F}_3 \\ \tilde{F}_4 \end{bmatrix} + B\, mg \qquad (3)$$

where

$$C_f = \begin{bmatrix} -1 & -1 & -1 & -1 \\ -R_f & R_f/2 & R_f/2 & 0 \\ 0 & -\sqrt{3}R_f/2 & \sqrt{3}R_f/2 & 0 \end{bmatrix}$$

$$B = [\,1 \;\; 0 \;\; 0 \;\; 0\,]^T$$

From Eq. (1) and (3), we have

$$\begin{bmatrix} \ddot{Z}_c \\ \ddot{\theta}_x \\ \ddot{\theta}_y \end{bmatrix} = C_m \times C_f \times \begin{bmatrix} \tilde{F}_1 \\ \tilde{F}_2 \\ \tilde{F}_3 \\ \tilde{F}_4 \end{bmatrix} + C_m \times B\, mg \qquad (4)$$

This is the general equation of motion of the wafer.

Electrostatic Attractive Force

In our experimental systems, the area of each of the outer three electrodes are the same, and the area of central electrode is three times that of a single outer three electrode. The bias voltage applied to the outer electrodes are positive, and the voltage applied to the central electrode is an average of the voltages applied to the outer electrodes, but has opposite polarity. Thus, the net potential of the wafer is maintained at zero voltage. Mathematically, the voltage relationship is

$$\tilde{V}_4 = -\frac{(\tilde{V}_1 + \tilde{V}_2 + \tilde{V}_3)}{3} \qquad (5)$$

Since the overlapping area of the electrodes and the wafer are large when compared to the gap, the respective capacitances can be expressed to a close approximation as

$$C_i = \frac{\varepsilon s}{\tilde{z}_i},\ (i = 1, 2, 3) \text{ and } C_4 = \frac{3\varepsilon s}{\tilde{z}_4} \qquad (6)$$

and the respective attractive force generated by four electrodes are

$$\tilde{F}_i = \frac{\varepsilon s \tilde{V}_i^2}{2\tilde{z}_i^2},\ (i = 1, 2, 3) \text{ and } \tilde{F}_4 = \frac{3\varepsilon s \tilde{V}_4^2}{2\tilde{z}_4^2} \qquad (7)$$

It is noted that the gap between the central electrode and the wafer can be calculated from the outputs of displacement sensors

$$\tilde{z}_4 = \frac{(\tilde{z}_1 + \tilde{z}_2 + \tilde{z}_3)}{3} \qquad (8)$$

Inserting Eqs. (5) and (8) into Eq. (7), we have

$$\tilde{F}_4 = \frac{3\varepsilon s(\tilde{V}_1 + \tilde{V}_2 + \tilde{V}_3)^2}{2(\tilde{z}_1 + \tilde{z}_2 + \tilde{z}_3)^2} \qquad (9)$$

Simplified Equation of Motion

When the suspension system is at the equilibrium state, the wafer is stably suspended under the electrode plate at the equilibrium gap z_e. The same positive voltages, V_e, are applied to the outer three electrodes and a negative V_e voltage is applied to the central electrode.

Next, let us simplify the above equations near the equilibrium state. First, we may express each of the variables as a sum of the value at the equilibrium state plus a variable term which is small compared with the equilibrium state magnitudes.

$$\begin{cases} \tilde{z}_1 = z_e + z_1, & \tilde{z}_2 = z_e + z_2 \\ \tilde{z}_3 = z_e + z_3 & \tilde{z}_4 = z_e + \dfrac{(z_1 + z_2 + z_3)}{3} \end{cases}$$

$$\begin{cases} \tilde{V}_1 = V_e + V_1, & \tilde{V}_2 = V_e + V_2 \\ \tilde{V}_3 = V_e + V_3, & \tilde{V}_4 = -V_e - \dfrac{(V_1 + V_2 + V_3)}{3} \end{cases}$$

With these formulae, we can simplify the force Eqs. (7) and (9) as

$$\begin{bmatrix} \tilde{F}_1 \\ \tilde{F}_2 \\ \tilde{F}_3 \\ \tilde{F}_4 \end{bmatrix} = C_l \times \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ 1 \\ 3 \end{bmatrix} F_e \qquad (10)$$

where

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} K_v - \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} K_z \tag{11}$$

$$C_l = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$F_e = \frac{\varepsilon s V_e^2}{2z_e^2}, \quad K_v = \frac{\varepsilon s V_e}{z_e^2}, \quad K_z = \frac{\varepsilon s V_e^2}{z_e^3} \tag{12}$$

It is obvious that in the equilibrium state, the following condition is satisfied.

$$6F_e = mg \tag{13}$$

Inserting Eqs. (10), (13) into (4), the simplified equation of motion of the wafer can be obtained.

$$\begin{bmatrix} \ddot{Z}_c \\ \ddot{\theta}_x \\ \ddot{\theta}_y \end{bmatrix} = C_m \times C_f \times C_l \times \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} \tag{14}$$

CONTROL STRATEGY

From Eq. (7), we can easily find that the attractive force is inversely proportional to the square of the gap between the electrode and the wafer, so the suspension system is inherently unstable without control of the applied voltages. In our experiment, a *local* control method, one in which the individual gaps at each outer electrode are controlled, is utilized as shown in Fig. 3. The outputs of three displacement sensors are respectively fed into three compensators as feedback signals. The compensators compare each signal with the reference value and regulate them using PD control. Next, the compensator outputs are amplified by dc high voltage amplifiers, and then applied to the respective outer electrodes. The mathematical description of this control strategy is as follows,

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = C_p \times \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + C_d \times \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} \tag{15}$$

where

$$C_p = \begin{bmatrix} K_1 & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & K_3 \end{bmatrix}, \quad C_d = \begin{bmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{bmatrix} \tag{16}$$

Combining Eqs. (11), (14), (15) and Eq. (2), we have

$$\begin{bmatrix} \ddot{Z}_c \\ \ddot{\theta}_x \\ \ddot{\theta}_y \end{bmatrix} - C_m \times C_f \times C_l \times C_{zd} \times C_s^{-1} \times \begin{bmatrix} \dot{z}_c \\ \dot{\theta}_x \\ \dot{\theta}_y \end{bmatrix}$$
$$- C_m \times C_f \times C_l \times C_{zp} \times C_s^{-1} \times \begin{bmatrix} z_c \\ \theta_x \\ \theta_y \end{bmatrix} = 0 \tag{17}$$

where

$$C_{zp} = \begin{bmatrix} K_1K_v - K_z & 0 & 0 \\ 0 & K_2K_v - K_z & 0 \\ 0 & 0 & K_3K_v - K_z \end{bmatrix}$$

$$C_{zd} = \begin{bmatrix} D_1K_v & 0 & 0 \\ 0 & D_2K_v & 0 \\ 0 & 0 & D_3K_v \end{bmatrix}$$

It is clear that for a proper choice of the matrices of control parameters defined in matrices (16), the system can be stabilized.

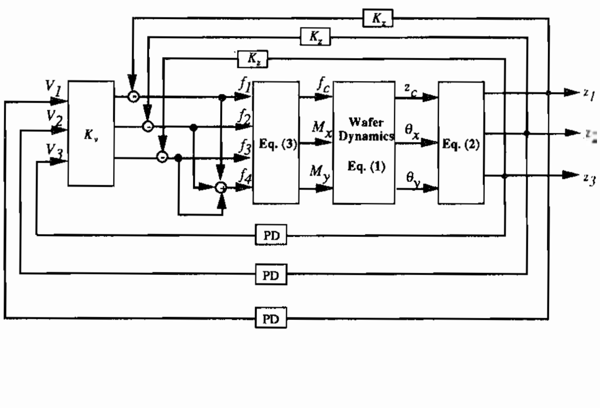

FIGURE 3 Local Control Strategy

EXPERIMENTAL WORK

Experimental System Configuration

The experimental system we have developed for suspending a silicon wafer is shown in Fig. 4. The four copper electrodes, as shown in Fig. 2, are formed on a plate by an etching process. The area of each of the three outer electrodes, which together form a ring, is about 12 cm^2, and the area of the circular central electrode is 36 cm^2. The electrode plate can be leveled by three micrometer positioning screws. The suspended object, a 9.1 g silicon wafer with 4 inch diameter, is initially placed on top of three additional micrometer positioning screws. Then by adjusting the heights of each micrometer positioning screw, the wafer can be leveled and the initial gap can be set. In our experiments, the initial gap was set to 410 µm. To measure position and orientation, three optical displacement sensors are located beneath the wafer. The sensor positions sit at the corners of an equilateral triangle which can be circumscribed by a circle of radius 45 mm.

Experimental Results

The experimental goal is to pick up and hold the wafer in a stable equilibrium position under the electrode plates at a gap of 400 µm, as can be verified by observing outputs of displacement sensors. The experimental conditions are shown in Table 2, and the experimental procedure is as follows: (1) The electrode plate is leveled by three micrometer positioning screws. (2) The wafer is leveled and placed under the electrode plate at a gap of 410 µm. (3) The dc high voltage amplifier are switched on , bias voltages of 670 V and -670 V are respectively applied to the outer and central electrodes. (4) The control units are switched on, control voltages are applied to electrodes, and the wafer is picked up. Fig. 5 shows the gap variations when control units are switched on. We can see from Fig. 5 that after a transient process, the wafer finally reached a stable equilibrium position. From the outputs of three sensors, the gaps at the three observing points are respectively 394, 396, 394 µm. Fig. 6 shows the voltage variations during the picking up process.

The suspension shown in Fig. 5 was achieved merely by proportional control. It is believed that there is a damping effect on the wafer as air is forced in and out of the gap. Since the gap is significantly smaller than the radius of the wafer, the air in the gap can be modeled as a squeeze film [8].

In addition, we have found that the motion of the wafer in the longitudinal and lateral directions are passively restricted. It is believed that the potential well that the wafer sits in during suspension conditions gives rise to this characteristic. This fact shows that the suspension unit can be incorporated into a moving system without

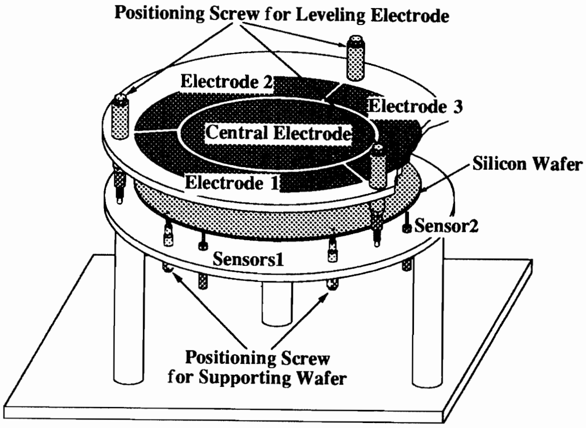

FIGURE 4 Experimental Wafer Suspension System

TABLE 2 Experimental Conditions

s	12 cm^2	V_e	670 V
m	9.1 g	K_1	23.8 V/µm
R_s	45 mm	K_2	23.8 V/µm
R_f	42.5 mm	K_3	23.8 V/µm
R_w	50 mm	D_1	0 V · s/m
I_x	56.9 g · cm^2	D_2	0 V · s/m
I_y	56.9 g · cm^2	D_3	0 V · s/m
Z_e	400 µm		

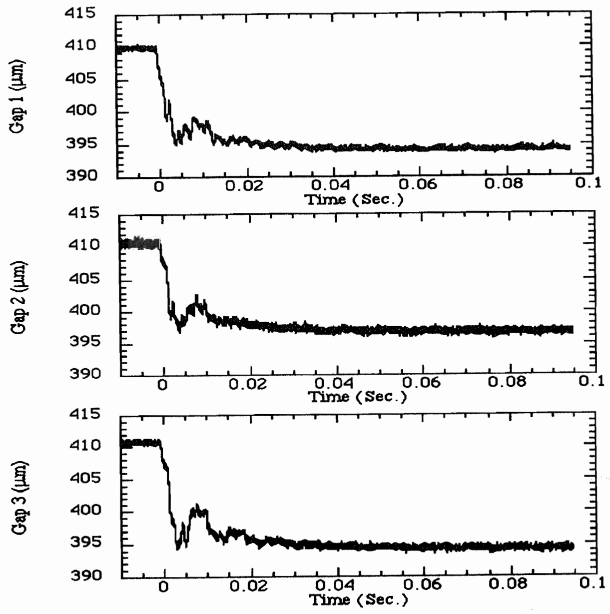

FIGURE 5 Gaps Between Electrode and Wafer

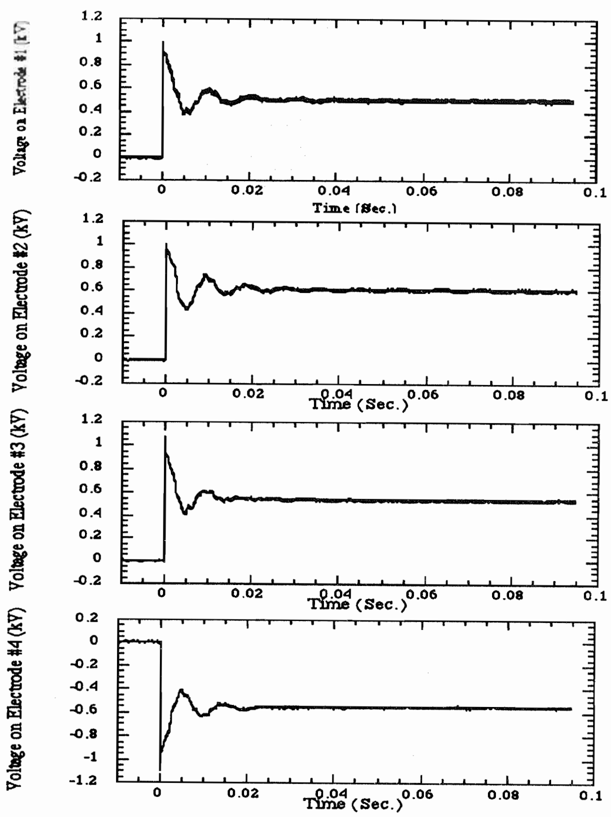

FIGURE 6 Voltages on Electrodes

additional mechanisms to prevent the wafer from "slipping" out of its suspended position in these passive degrees-of-freedom.

We also have succeeded in suspending a hard disk media with diameter 95 mm using electrostatic force.

CONCLUSION

A silicon wafer has been suspended successfully by controlling an electrostatic force acting on it. This achievement now opens the door to develop contact-less wafer manipulators for use in Ultra-High-Vacuum (UHV) and ultra clean environments, both of which are necessary for manufacture of the new generation semiconductor devices. We believe that this research can find wide industrial applications in the future.

REFERENCE

[1] J. Jin and T. Higuchi, "Self-sensing electrostatic suspension", *Proceedings of the International ISEM Symposium on Simulation and Design of Applied Electromagnetic Systems*, p. 607- 610, 1993.

[2] J. Jin, "Magnetic suspension using tuned LC circuit", Doctoral Thesis, University of Tokyo, 1992.

[3] H. W. Knoebel, "The electric vacuum gyro", *Control Engineering*, Vol. 11, p. 70-73, 1964.

[4] S. Kumar, D. Cho, et al, "Experimental Study of Electric Suspension for Microbearings", *Journal of Microelectromechanical Systems*, Vol. 1, No. 1, p. 23- 30, 1992.

[5] B. V. Jayawant, "Electromagnetic Levitation and Suspension Techniques", Edward Arnold, 1981.

[6] R. H. Frazier, P. J. Gillinson, and G. A. Oberbeck, "Magnetic and electric suspensions", Cambridge, Mass., MIT Press, 1974.

[7] E. H. Brandt, "Levitation in Physics", *Science*, Vol. 243, p. 349-354, 1989.

[8] W. S. Griffin, H. H. Richardson and S. Yamanami, "A study of fluid squeeze film damping", *ASME J Basic Eng.*, p. 451-456, 1966.