Direct Electrostatic Levitation and Propulsion of Silicon Wafer

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Abstract — *A new type of contact-less wafer manipulator, featuring "Direct Electrostatic Levitation and Propulsion of Silicon Wafer" (DELP-SW), has been successfully developed. The novel aspect of this manipulator is that a silicon wafer can be directly levitated and driven via electrostatic forces. In this paper, a brief review of basic principles is presented. This is followed by a description of the structure of a prototype DELP-SW mechanism, including electrode design, position feedback control method, driving principle and the operational procedure. Experimental results which demonstrate completely contact-less transportation of a 8-inch silicon wafer are also presented.*

1. Introduction

In manufacturing processes for highly-integrated semiconductor devices and LCDs, contamination of product surfaces by dust particles is a major factor restricting the product yield [1], [2]. To prevent triboelectrification, contact electrification, and the generation and adhesion of frictionally-produced dust particles, contact-less manipulation of semiconductor wafers and LCD glass plates is desirable. In addition, in order to avoid electron and ion transfer during the synthesizing process of pure materials, it is necessary to hold and handle the sample without any physical contact with other materials.

To date, the transport and handling of wafers and glass plates have mainly been done by robots equipped with carrier spatulas. The physical contact and friction between the object and the carrier spatula not only produces dust particles, but also gives the transported object a charge which further attracts dust particles from the working environment.

Magnetically levitated manipulators and transportation apparatus have been developed to meet these requirements [3], [4]. However, since a magnetic force cannot suspend silicon wafers or other non-ferromagnetic metals directly, the object is typically supported on the carrier spatula during transportation process. Therefore, this class of manipulators and apparatus is friction-free but not contact-less, and cannot solve the problems mentioned above.

In this paper, we propose a new type of contact-less mechanism called "Direct Electrostatic Levitation and Propulsion". The novel aspects of this mechanism are that it not only can directly levitate and drive semiconductors and other non-ferromagnetic metal materials via electrostatic forces, but also can keep their net surface charges near zero volts. As a result, it can reduce greatly the contamination of product surfaces by dust particles.

2. DELP-SW Mechanism

2.1 Configuration of DELP-SW

Figure 1 shows the schematic view of the prototype DELP-SW mechanism. The mechanism is composed of :

1) Electrode plate: producing levitating and driving force;
2) 8-inch silicon wafer: object to be transported;
3) Displacement sensors (eight): measuring gaps between electrodes and wafer;
4) DSP-based controllers: controlling voltages applied to electrodes;
5) High voltage DC amplifiers (four): amplifying outputs

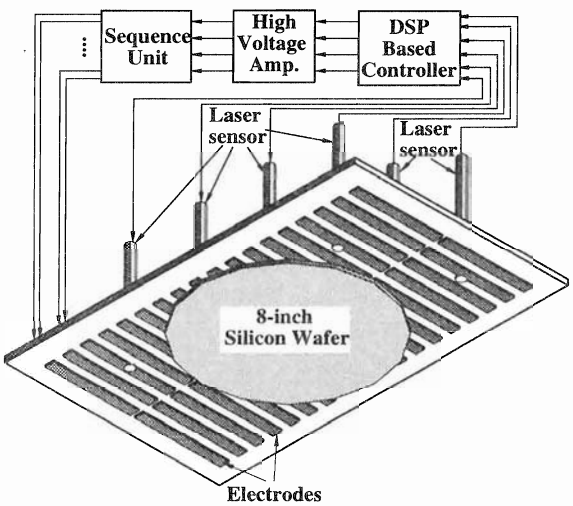

Fig. 1 Schmatic of DELP-SW

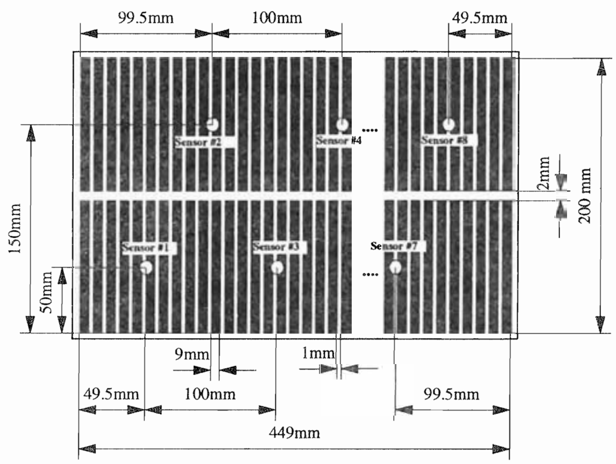

Fig. 2 Electrode pattern

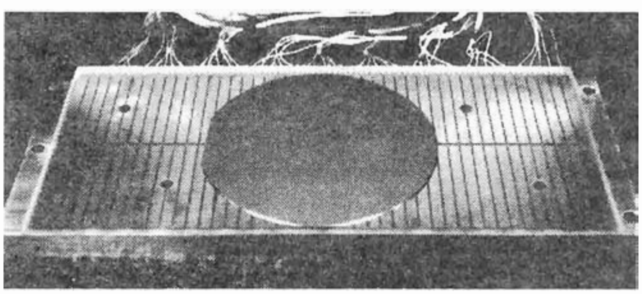

Fig. 3 Photograph of electrodes and 8-inch wafer

of controllers by 1000 times;

6) Sequence unit: controlling voltage-application sequence.

The transported object is a silicon wafer with 8 inch diameter, 0.71 mm thickness, and 51.5 g mass.

The electrode plate, as shown in Fig. 2, is fabricated from a glass epoxy PCB. Two copper electrode structures, separated by a 2 mm wide insulating gutter zone, are formed by an etching process. Each structure consists of 45 strip electrodes with 9 mm widths and arranged periodically at 1 mm gaps. The corners of each strip electrode are rounded off to prevent charge

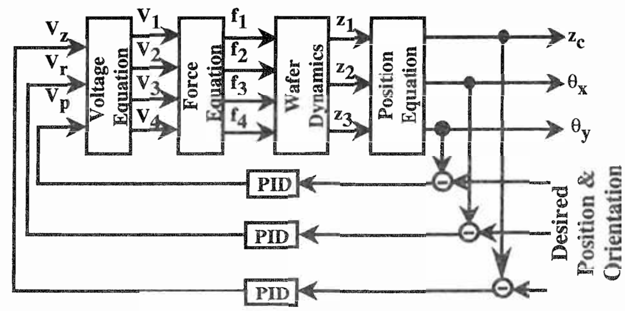

Fig. 4 Integrated control strategy

concentration. Additionally, for the purpose of restricting the lateral movement of wafer during levitation state and driving process, the electrode part width is designed to equal to the wafer diameter, i.e. 200 mm. Eight holes, for laser displacement sensors, are opened evenly in the positions shown in Fig. 2.

2.2 Principle of Levitation

In order to hold the wafer horizontally, it is necessary to control its movement in five degrees-of-freedom: movement in horizontal plane (2 degrees-of-freedom), movement in vertical direction, pitching and rolling. Among them, the movement in horizontal plane is passively restricted by lateral force, which occurs under the following two conditions: (i) voltages are applied only upon the electrodes overlapping with the wafer, and (ii) the wafer has a relative displacement with respect to the electrodes.

The remaining three degrees are actively controlled. An integrated control method, one in which the position and orientation of the wafer are controlled, is utilized, as shown in Fig. 4. The equations of motion for the wafer and the integrated-control system equations have been developed in [7]. Here only its operation principle is briefly described as follows:

1) From the outputs of three displacement sensors, for example, sensors #1, #2 and #3, (Z_1, Z_2, Z_3), the wafer's position information in the vertical direction Z_c, as well as the rolling angle θ_x and pitching angle θ_y, are calculated.
2) The position and orientation information are fed into three Proportional-Integral-Derivative (PID) controllers as feedback signals. Controllers generate error signals by comparing the input signals with the reference values, and calculate the error signals by PID algorithms to compute three output signals (V_z, V_r, V_p).
3) Then, the three output signals are separated into four signals. Together with a bias voltage V_e, two positive control signals V_{c1}, V_{c4} and two negative control signals

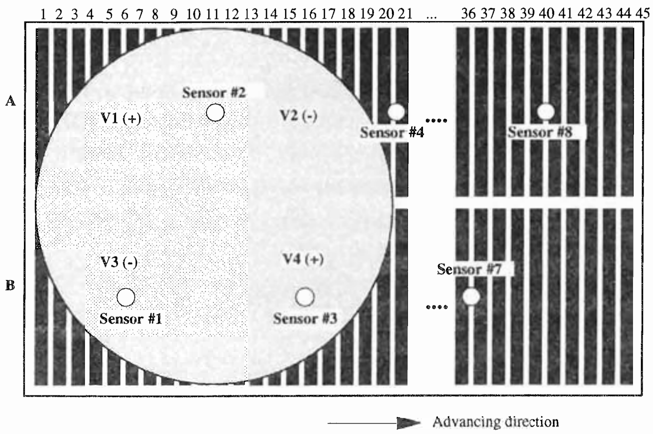

Fig. 5 Relative position of electrodes and wafer (bottom view)

V_{c2}, V_{c3} are generated, as represented in (1).

$$\begin{cases} V_{c1} = \left[V_e + (V_z/4 - V_r/2 + V_p/2)\right] \\ V_{c2} = -\left[V_e + (V_z/4 - V_r/2 - V_p/2)\right] \\ V_{c3} = -\left[V_e + (V_z/4 + V_r/2 + V_p/2)\right] \\ V_{c4} = \left[V_e + (V_z/4 + V_r/2 - V_p/2)\right] \end{cases} \quad (1)$$

4) Next, the four control signals are respectively amplified 1000 times by four DC amplifiers to generate two positive high voltages V_1, V_4, and two negative high voltages V_2, V_3, as expressed in (2).

$$\begin{cases} V_1 = 1000\left[V_e + (V_z/4 - V_r/2 + V_p/2)\right] \\ V_2 = -1000\left[V_e + (V_z/4 - V_r/2 - V_p/2)\right] \\ V_3 = -1000\left[V_e + (V_z/4 + V_r/2 + V_p/2)\right] \\ V_4 = 1000\left[V_e + (V_z/4 + V_r/2 - V_p/2)\right] \end{cases} \quad (2)$$

5) Finally, the four high voltages V_1, V_2, V_3, V_4 are evenly applied to the strip electrodes which are overlapping with the wafer, as shown in Fig. 5, which shows the relative position of the wafer and the electrodes. In detail, the voltages are applied in the following way: V_1 is applied to electrodes A1-A10, V_2 to A11-A20, V_3 to B1-B10 and V_4 to B11-B20. As a result, both positive and negative charges are induced on the wafer surface. This in turn generates four electrostatic forces, f_1, f_2, f_3, f_4, as shown in Fig. 4, and the wafer is picked up from its initial position to the stable suspension state.

2. 3 Principle of Zero Surface Charge

The surface potential of the wafer can be calculated from the following equation:

$$V_{wafer} = \frac{\sum_{n=1}^{4} C_i V_i}{\sum_{n=1}^{4} C_i} \quad (3)$$

where C_i is the capacitance between the wafer and the electrodes with voltage V_i.

When the wafer is levitated horizontally in the equilibrium position, (i) the outputs of three PID controllers, V_z, V_r, V_p, all are zero, and from (2) , we have

$$V_1 = V_4 = 1000\, V_e, \quad V_2 = V_3 = -1000\, V_e \quad (4)$$

(ii) the capacitances have the same value of the equilibrium capacitance, C_e, i.e.,

$$C_1 = C_2 = C_3 = C_4 = C_e \quad (5)$$

It is not difficult to find from (3), (4) and (5) that

$$V_{wafer} = 0 \quad (6)$$

The net potential of the wafer is maintained at zero volt, thus preventing surface adhesion by dust particles and discharge accidents.

2.4 Driving Principle

2.4.1 Voltages Switching: When the wafer is in its stable suspension position, it stays under the electrodes A1-A10, and B1-B20, as shown in Fig. 6 (a), which is a side view showing the relative position of the electrodes and the wafer. To drive the wafer during its suspension state, the electrostatic field can be moved in the advancing direction. In detail, The voltages V_2, V_4 are applied to the strip electrodes A21 and B21, both of which are nearest to the wafer on side of the advancing direction, but not overlapping it. At the same time, The voltages V_1, V_3 to the strip electrodes A1 and B1, both of which are the outermost electrodes that overlap with the wafer on the side opposite to the advancing direction, are cut off. Furthermore, the voltages to the electrodes A11 , B11 are respectively changed from V_2 to V_1, and V_4 to V_3. As a result, the electrostatic field moves one pitch, and driving forces shown in Fig. 6 (b) arise. They draw the wafer forward one step equal to one strip electrode, as shown in Fig. 6 (c). By repeating this process, the wafer can be transported continu-

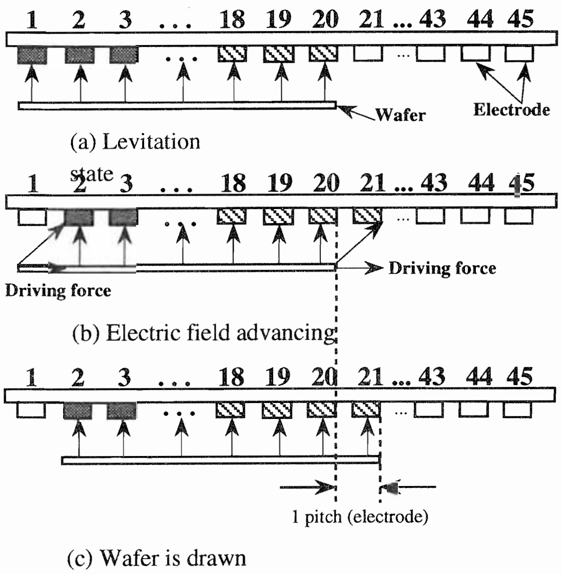

Fig. 6 Relative position of elctrodes and wafer (side view)

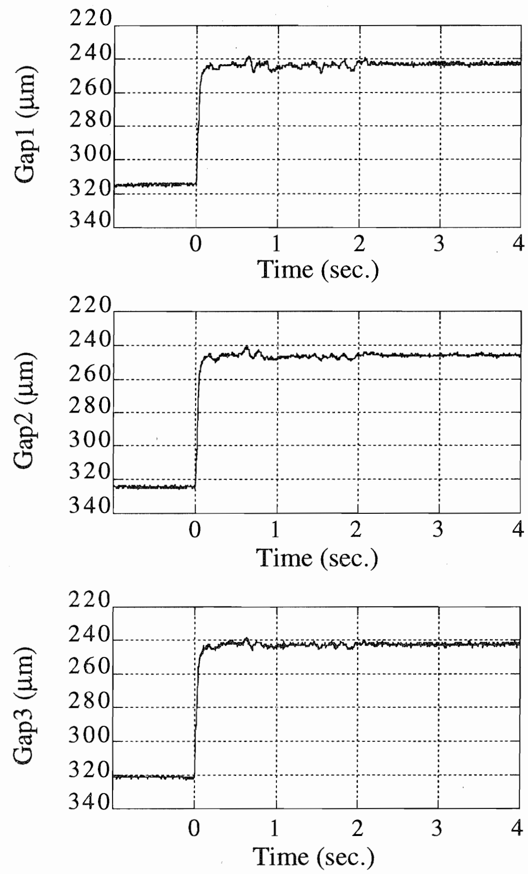

Fig. 7 Gaps variation during levitation process

ously four pitches without suspension failure.

2.4.2 Selecting Sensors: To advance the wafer furthermore, displacement sensors #2, #3 and #4 are selected to measure the position and orientation of the wafer. Because the sensor #1 can no longer cover the wafer at the next step. From the outputs of three displacement sensors #2, #3 and #4, (Z_2, Z_3, Z_4), the DSP-based controller generates the new values of voltages, V_1, V_2, V_3, V_4, based on the control law described in the section 2.2. Then by repeating the "voltages-switching" process described in the section 2.4.1, the wafer will be propelled furthermore.

By repeating the above two procedures, the wafer can be continuously transported in a way of contact-less.

3. Experimental Works

Using the DELP mechanism described in section 2.1, we carried out a levitation and propulsion experiment for a 8-inch silicon wafer in the atmospheric environment. The experimental procedure is as follows.

3.1 Leveling Wafer and Setting Initial Gap

First, we placed the wafer horizontally under electrodes A1-A20 and B1-B20, at an initial gap of 320 μm.

3.2 Picking Up Wafer

The second step is to pick up the wafer from its mechanical supporter and stably levitate it under the electrode plate at a gap of 250 μm. The voltage-applying procedure is: (1) switching on the high voltage DC amplifiers; and (2) switching on the DSP-based controllers, applying voltage V_1 to electrodes A1-A10, V_2 to electrodes A11-A20, V_3 to electrodes B1-B10, and V_4 to electrodes B11-B20. When the voltages applied to the above electrodes became greater than the threshold voltage, the wafer moved away from its mechanical supporter upwards to the equilibrium position. In this context, the threshold voltage means the voltage necessary for balancing the weight of the wafer at the initial gap of 320 μm. This process can be verified from Fig. 7, which shows the gaps variation after the PID controllers had been switched on. We can note from Fig. 7 that the outputs of three displacement sensors change respectively from 315 to 244, 324 to 248, and 321 to 244 μm. Compared to the desired gap 250 μm, The maximum position error is 6 μm.

Fig. 8 shows voltages variation during the picking up process. When the wafer was in stable suspension state, the four high voltages, V_1, V_2, V_3, V_4, are respectively 577, -551, -502 and 483 V.

Fig. 9 illustrates the surface potential of the wafer during the picking up process. It is found that the maximum potential appeared on the wafer surface is -25 volt, and the residual

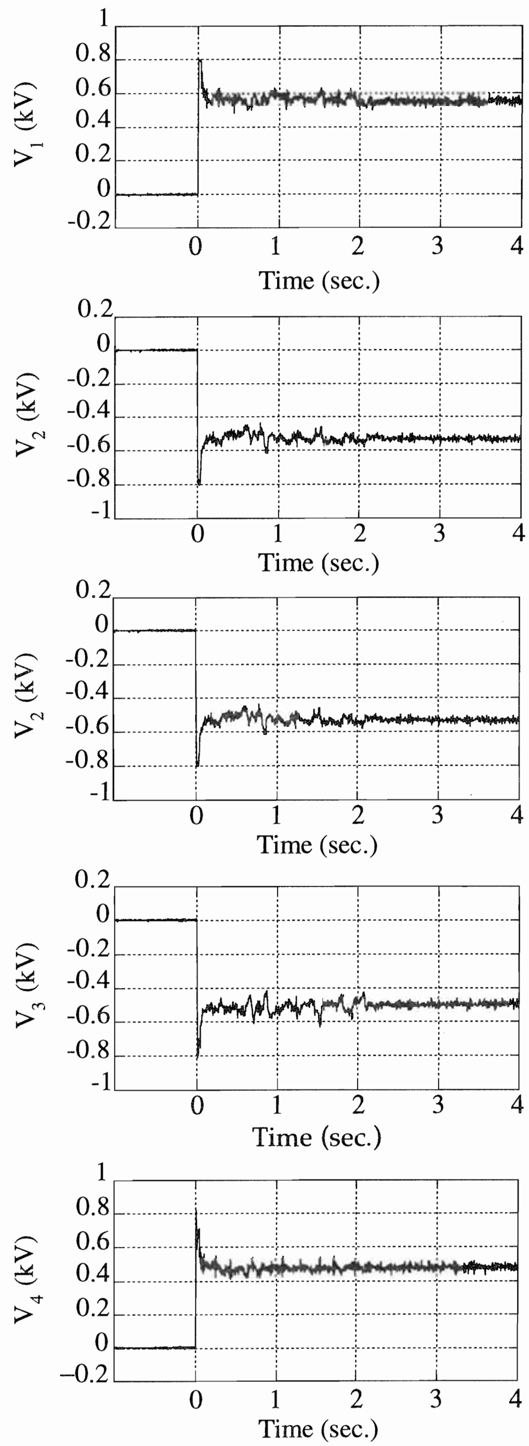

Fig. 8 Voltages variation during picking up process

potential is about -7 volt when the wafer reached its stable suspension state. Because particle attraction generally occurs in the kilovolt order [8], the -25 volt potential level has a negligible impact on particle contamination.

3.3 Propelling Wafer

The third step is to drive the wafer during its suspended state. The wafer's horizontal movement was recorded by a laser dis-

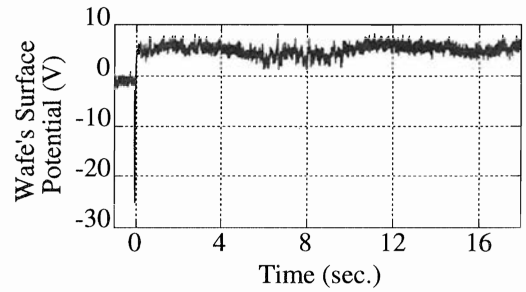

Fig. 9 Surface potential of wafer during picking up process

placement sensor. In this paper, we investigated the first five pitches movement. The driving procedure is as follows:

1) At the start of our experiments, the wafer was initially suspended under electrodes A1-A20 and B1-B20.

2) Then, voltage V_2 (-551 V) was applied to electrode A21, voltage V_4 (483 V) to electrode B21, and voltage V_1 (577 V) to electrode A1 and V_3 (-502 V) to electrode B1 were cut off. At the same time, voltage to electrode A11 was changed from V_2 to V_1 and voltage to electrode B11 was changed from V_4 to V_3. Consequently, the electric field and thus the wafer moved one pitch (10 mm).

3) After 3 seconds, voltage V_2 was applied to electrode A22, voltage V_4 to electrode B22, and voltage V_1 to electrode A2 and V_3 to electrode B2 were cut off. And the voltage to electrode A12 was changed from V_2 to V_1 and the voltage to electrode B12 was changed from V_4 to V_3. The wafer moved one more pitch.

4) Next, the displacement sensors (#2, #3, #4), instead of (#1, #2, #3), were selected to measure the position and orientation of the wafer. From the outputs of the above three sensors, the DSP-based controller calculated again the values of the four voltages (V_1, V_2, V_3, V_4), according to the principle described in section 2.2, and thus maintained the stable levitation state of the wafer.

Then, voltage V_2 was applied to electrode A23, voltage V_4 to electrode B23, and voltage V_1 to electrode A3 and V_3 to electrode B3 were cut off. And the voltage to electrode A13 was changed from V_2 to V_1 and the voltage to electrode B13 was changed from V_4 to V_3. As a result, the wafer moved forward another pitch.

By repeating the above processes using the sequence shown in Fig. 10, the wafer was driven continuous forward. Finally, it stayed under the electrodes A6-A25 and B6-B25. This horizontal displacement of the wafer was shown in Fig. 11, and Fig. 12 is a photograph showing the wafer during contact-less transportation.

It is found from Fig. 11 that: (i) it took 5.6 seconds for the

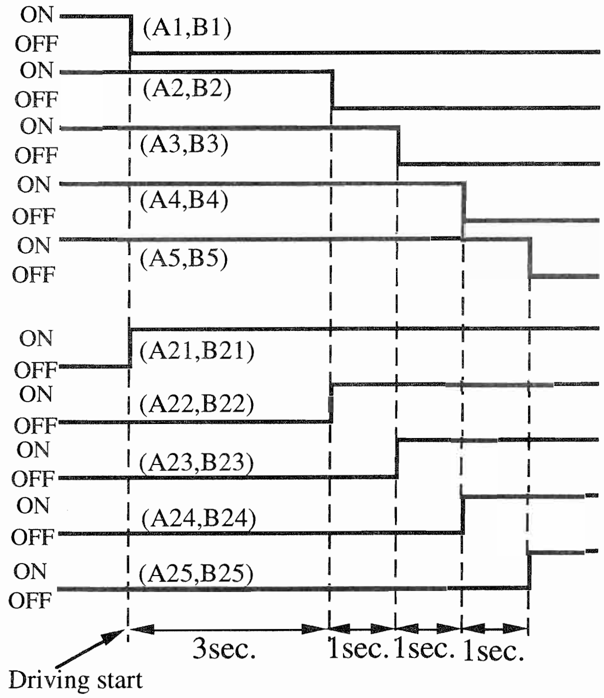

Fig. 10 Voltages-applying seqence

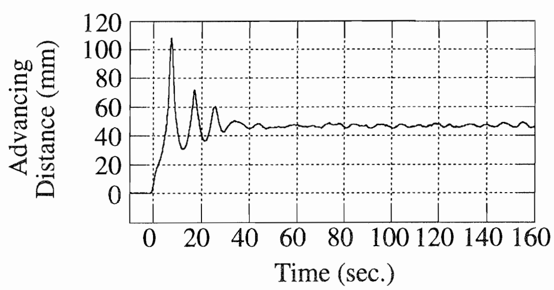

Fig. 11 Movement of wafer in horizontal direction

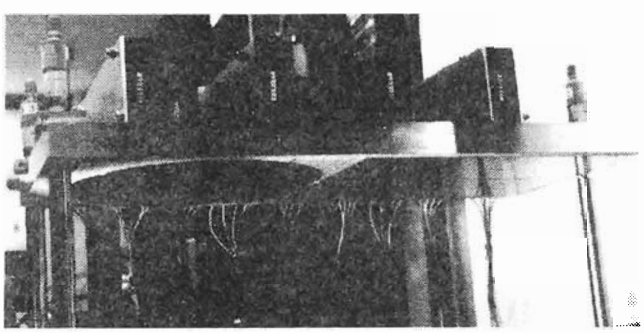

Fig. 12 Wafer during contact-less transportation

wafer to pass by the first five pitches (50 mm); (ii) the maximum overshoot was 58 mm; (iii) it took as long as one minute for the wafer to reach the desired horizontal position. This is due to that in the horizontal direction, the main brake exerted to the wafer was the friction between the air and the wafer , which is generally not so strong. The slow positioning in the horizontal direction is one of the major problems restricting the practical applications of the DELP-SW mechanism. Because it greatly affect the efficient of the transportation.

4. Conclusions

In this paper, a newly developed mechanism, "Direct Electrostatic Levitation and Propulsion of Silicon Wafer" mechanism, together with the basic principles of electrostatic suspension, electrostatic driving, electrode design, position feedback control method, have been described. A 8-inch silicon wafer, with 51.5 g mass, has been suspended and transported successfully in the atmospheric environment. This mechanism has the potential to become the first generation of contact-less wafer transportation equipment and manipulators in UHV and ultra clean environments, both of which are necessary for the manufacture of the new generation semiconductor devices.

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