Manipulation by dipole probe

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Abstract

A dipole probe is fabricated to manipulate millimeter- to submillimeter-sized objects. A tungsten needle, an alumina tube and a stainless tube are arranged concentrically in order inside the probe. The tip of the stainless tube is ground to form a needle. They are embedded in an epoxy resin and the tip of the probe is shaped hemispherically. The probe has two electrodes, a tungsten needle and a stainless steel needle, inside it. The probe can attract objects by gradient force like a bipolar electrostatic chuck. The attraction force is measured as a function of the applied voltage, and they are compared with those calculated by a 3D FEM. Both the experimental values and the calculated values are proportional to the square of the applied voltage. The determined values are, however, three times greater than those by the calculated values. The difference is ascribed to the incomplete shape of the probe model and the difference of dielectric constants of materials. The probe can attract both conductive gold particles and dielectric foam styrene particles. The probe is placed above the particle and a voltage supplier is turned on. The particle jumps up and adheres at the tip of the probe. The adhesive position is not on the center axis of the probe but the opposite side to the stainless needle against the center of the probe. The distances from the center of the probe are at a range of 0.4–1.05 mm for 20 experiments. The FEM calculation shows that maximum attraction force is for the particle placed at the opposite side to the stainless needle. Release is possible only by turning the voltage supplier off. The particle moves to the bottom of the probe, and falls after 1–2 s. The delay is due to the attenuation period of electrons accumulated at the surface of the probe.

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1. Introduction

Attention has focused on the manipulation of fine objects [1] due to the recent development of biology, electronics, and tele-surgery. Different from the self-assembly, the method manipulates fine objects one by one. The manipulation method is, therefore, not efficient, but it can make arrangements at a precise point under the complete control of an operator.

Various methods of such a ‘one-by-one manipulation’ are investigated. Laser manipulation traps and moves fine objects using the radiation pressure. As the holding force is weak, it can apply only to the manipulation of micrometer-sized objects floated in a liquid [2] or nanometer-sized particles [3]. Various holding tools are used to manipulate millimeter- to submillimeter-sized objects, such as a capillary tube [4], microgripper [5], chopsticks [6], needle-like probe [7], etc. The capillary tube holds fine objects by suction, the microgripper/chopstick by friction, and the probe by adhesions.

The former three can easily control the holding force. On the other hand, the adhesions of the probe are difficult to control the intensity. The probe has, however, advantages that the structure is simple and free from mechanical trouble. Adhesions of the probe mainly consist of van der Waals force, liquid bridge force, and electrostatic force [8]. They are always generated when two substances are in touch. As the adhesions are weak, particles above 10 μm are difficult to pick up by the probe. Our idea is using an external electric power source to enhance the electrostatic force. The intensity of the holding force will be controlled by the external electric power. One advantage of the method is overcoming the disadvantage without loss of the advantage.

The principle is the same with electrostatic chucks (ESCs), which are used mainly to hold silicon wafers in the semiconducting industry. They are classified to monopolar type and bipolar type according to the number of electrodes [9]. Two types of probe are, therefore, possible corresponding to the type of the ESC. The monopolar type of probe contains one electrode and the bipolar type contains two electrodes, an applied electrode and a counter electrode.

The monopolar type is called a monopole probe, and the bipolar type is called a dipole probe in this paper. We have
already reported on the performance of the monopole probe [10], of which the electrode is the probe itself. This paper describes experiments on the manipulation by the dipole probe and calculations of the adhesions.

2. Experiments

2.1. Dipole probe

Fig. 1 shows the structure of the dipole probe. The applied electrode and the counter electrode are a tungsten needle and a stainless needle, respectively. The tungsten needle of 0.66 mm in diameter and the stainless tube of 1.5 mm inner diameter and 2.5 mm outer diameter are arranged concentrically, and an alumina tube is inserted in between for insulation. The tip of the stainless tube is ground to form a needle to equalize the size with the tungsten needle.

The electrodes and the insulator are embedded in an epoxy resin (EPO-TEK 302, Epoxy Technology Inc.) and the tip of the probe is shaped hemispherically. The length and outer diameter of the probe is 24 mm and 3.1 mm, respectively.

2.2. Measurement of attraction force

Attraction force of the dipole probe is measured as shown in Fig. 2. A glass tube, of which both ends are each connected with a gold wire of 0.3 mm in diameter, is prepared. It is hung from the back of a weighing pan of an electronic balance (AE163, Mettler-Toledo K.K.) using one end of the gold wire. The bottom end of another wire is melted to form a ball of 1.2 mm in diameter. The probe is placed upside-down faced to the gold ball with a small gap. The force, by which the probe attracts the gold particle, is obtained as a weighing result of the balance.

A preliminary experiment showed that electric fields of the probe did not affect the weighing results, if the probe is placed 180 mm far from the weighing pan. The distance between the probe and the balance is, therefore, set to be 200 mm. A solder wire of 15 g is coiled around the glass tube to avoid the tremble.

2.3. Catch and release

The probe is vertically placed above a particle on a substrate, and a DC voltage supplier is turned on. The tip of the probe is observed by a video camera through a magnifying glass of 4 times magnification to ensure the results whether the particles are caught or not. The break-down voltage of the probe is estimated to be 6.7–9.2 kV from the dielectric breakdown strength of the epoxy resin of 16–22 MV/m. The applied voltage is, therefore, limited to 6 kV.

2.4. Simulation

The attraction force is calculated by a three-dimensional field simulator (Maxwell, Ansoft Co.) using the finite element method (FEM) and the results are compared with the determined values. The total charge of the gold sphere and other materials including glass tube and solder wire is assumed to be 0 in the calculations. The FEM calculation is conducted within 500% space of the probe. Potential of the border plane is assumed to be 0.

2.5. Materials

Both a conductive particle and a dielectric particle are examined for the catch and release experiments of the probe. The former is gold particles of ca. 0.4 mm in diameter and the latter is foam styrene particles of ca. 3 mm in diameter.
The experiments are conducted for the particles on a quartz plate substrate of 1 mm in thickness.

3. Results and discussion

3.1. Effect of applied voltage on attraction force

The attraction force exerted on the gold particle is measured by the method described in Section 2.2. The gap between the probe and the particle is fixed to be 0.4 mm. The results are shown by the white circles in Fig. 3. Attraction force, \( F \), is plotted against the applied voltage, \( V_a \), in Fig. 3. The experimental data are approximately represented by a solid curve expressed by Eq. (1).

\[
F = 4.40V_a^2
\]  

(1)

Calculated values by the three-dimensional field simulator are represented by a dotted line, expressed by Eq. (2)

\[
F = 1.59V_a^2
\]  

(2)

The index of \( V_a \) is equal to 2 in Eq. (1) and in Eq. (2), meaning that the attraction force is proportional to the square of the applied voltage. The same dependency is obtained in another study [11], in which the attraction force between a conductive column and a conductive sphere is calculated by the boundary element method (BEM).

The coefficient of Eq. (1) is about three times greater than that of Eq. (2). Two major reasons are considered for the difference of the coefficients. One is the similarity of the probe model. The shape of the probe is read out from the magnified pictures to draw an accurate model. The real shape is, however, represented by the aggregation of many tetrahedra-shaped regions (elements). A curved surface is, therefore, always approximated to planes. In particular, the difference from irregular surface of the stainless needle, which is ground by hand, is not negligible. The asperity of the electrode affects the distribution and concentration of electric field and it caused the difference of real attraction force and calculated attraction force.

The other is dielectric constant of materials. We use the values of database attached to the simulator. The dielectric constants of epoxy resin and alumina, however, rather vary dependent upon the preparation conditions. Our calculation shows that a difference of 10% in dielectric constant causes about 10% deviation of calculated values.

The simulation cannot be used to obtain the intensity of the attraction force, but to grasp the tendency. For example, it will be useful to decide the best shape and arrangement of the electrodes.

3.2. Effect of distance on attraction force

The attraction force exerted on the gold particle of 1.2 mm in diameter is calculated as a function of gap, \( L \), between the probe and the particle. The solid curve in Fig. 4 shows the calculated values for the constant applied voltage of 5 kV. The line is expressed by Eq. (3).

\[
F = 12.0L^{-1.02}
\]  

(3)

The attraction force is almost inversely proportional to the gap. Assuming the attraction force is about three times greater than the calculated value similar to Fig. 3, the probe must be positioned within 0.2 mm from the 1.2 mm gold particle to attract it.

3.3. Catch particles by dipole probe

The dipole probe is vertically placed above the gold particle or the foam styrene particle on the quartz substrate. Then, the voltage supplier of the probe is turned on to examine the performance of the probe.

The foam styrene particle jumps up and adheres at the tip of the probe, when the gap between the probe and the particle is 1 mm and voltage is 2 kV. For the gold particle, 5 kV is required to jump over the gap of 0.5 mm. Fig. 5(a) and (b) are frames of the video camera, in which the probe adheres the foam styrene particle.
particle and the gold particle, respectively. The center of gravity of the particle is not on the center axis of the probe.

The applied electrode is positioned on the center axis of the probe, and the counter electrode of the stainless needle is in the right side of the probe in the photographs. The attraction center is, therefore, opposite side to the counter electrode against the center of the probe.

Adhesive position is accurately measured from the video pictures. All particles independent of the kind are adhered at a narrow range of 0.4–1.05 mm from the center axis of the probe to the opposite direction. The mean value of 20 experiments is 0.73 mm and the standard deviation is 0.14 mm.

The attraction force is calculated again for 1.2 mm gold particle. Similar to those shown in Figs. 3 and 4, the applied voltage and the gap is fixed to 5 kV and 0.4 mm, respectively. The position of particle is varied horizontally from the center of the probe to left side and right side. The results are shown in Fig. 6. The origin of the horizontal axis is the position of the applied electrode, and the counter electrode is positioned at \( C + 1 \) mm.

Calculated data are shown by white circles and the solid curve is drawn by the least square method. The white circles are slightly scattered around the solid curve. Meshes of the FEM calculation are generated automatically by the simulator, and the calculation is finished automatically by judging the convergence. The final value of the calculation is affected by the initial conditions. That is the reason why the calculated data are not completely on the smooth curve.

The maximum value of the attraction force is at about -0.4 mm. The calculation is conducted for the particle 0.4 mm apart from the probe. The intensity of the attraction force, therefore, does not directly reflect the adhesive position. The results in Fig. 6, as a whole, support the observation shown in Fig. 5.

### 3.4. Release particles from dipole probe

The voltage supplier is turned off. The particle then slides to the bottom of the probe and falls after the probe holds it for 1–2 s at the bottom. As the attenuation rate is slow for the epoxy resin, accumulated electrons at the surface of the resin disappear not at once. The holding time of 1–2 s corresponds to the attenuation period of the electrons.

The particle should fall immediately after turning the voltage supplier off from the practical viewpoint. Adhesions are always a problem for handling of fine particles. Proposed methods for immediate release \[4,12\] are to add vibration to the holding tool, to short-circuit the electrodes, to remove adsorbed water by heating, to reverse the polarity of the electrodes, to control the surface roughness, and to select the materials of the probe. Among these methods, the latter three will be effective for our probe.

The particle is attracted at a position slightly apart from the center axis of the probe. As it falls after moving to the center, the particle can be placed just below the center of the probe. The adhesive position should be, however, just at the tip of the probe. It is solved by modification of the position and shape of the electrodes. For this sake, calculation by FEM is helpful.
3.5. Features of dipole probe

The dipole probe is regarded as a miniaturized bipolar type ESC having interdigitated electrodes. The attraction force is, therefore, considered to be gradient force [9]. The disadvantage of the bipolar type ESCs is that the clamping force is smaller than that of monopolar type ESCs. However, it is not a disadvantage for the dipole probe, because the objects are extremely small and light.

The monopole probe corresponding to the monopolar type ESCs requires a metallic substrate as a counter electrode, i.e., the objects should be put on a metallic substrate for the manipulation by the monopole probe. On the other hand, the dipole probe can manipulate objects on any substrate. As the dipole probe generates the attraction force without any net charge flow, it can be applied to manipulation of mechanical parts and electronic parts, except for those susceptible to electrostatic shock.

Miniaturization of mechanical and electronic parts continues every year, and a new handling technology will be required in the near future. The dipole probe is one of the solutions.

4. Conclusion

A dipole probe, in which two electrodes are equipped, is fabricated to manipulate millimeter- to submillimeter-sized objects. Although the monopole probe can handle small objects only on a metallic substrate, the dipole probe can handle without any limitation of substrates. Experiments of catch and release were carried out using conductive particles and dielectric particles. The attraction force is obtained by measurement and also by calculation of the FEM. The results are as follows.

(1) The attraction force of the probe is proportional to the square of applied voltage. This relation is obtained by the experiments and the calculations. The values of the attraction force obtained by the experiments are three times greater than those by the calculations. The difference is ascribed to the difference of drawing model and dielectric constant values of the probe materials.

(2) Both the conductor of a 0.4 mm gold particle and the dielectrics of a 3 mm foam styrene particle can be attracted by the probe. They jump up to the probe and adhere at the tip of the probe.

(3) Both a gold particle and a foam styrene particle adhere at a range of 0.4 – 1.05 mm from the center axis of the probe (applied electrode) to the opposite direction of counter electrode. This observation agrees with the results of the calculation by FEM.

(4) By turning the voltage supplier off, the particle slides to bottom of the probe, and it falls after 1 – 2 s. The delay is due to the attenuation period of the electrons accumulated on the surface of the dipole probe.

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