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Assembling Process of Particles by Electric Potential Field

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We have been developing a new technique to assemble microscale particles for the fabrication of two-dimensionally controlled microstructures. The procedure is as follows: An electrified pattern is formed on a dielectric substrate by the scanning of charging beams. The substrate is then dipped into a suspension in which the particles are dispersed. The particles migrating to the pattern are arrayed on the substrate. However, details of the electrostatic force causing migration of the particles in the suspension are not clear.

In this paper, we investigated the electrostatic force from both the experimental and theoretical viewpoints. Spherical silica particles of 5μm diameter were used as a model. The particles were negatively charged in the suspension and the ζ potential was −66mV. The particles were deposited on both the negatively and positively charged patterns. This experimental result suggests that the gradient force plays an important role in attracting the particles. The electrostatic forces for the particles in the suspension were calculated using a numerical analysis method. This calculated results showed that the gradient force is stronger than Coulomb's force near the electrified pattern.

Key words: Particle Assembly, Electrification, Micro-sized particle, Coulomb's force, Gradient force

1. INTRODUCTION

The assembly of particles is one of the built-up methods for the fabrication of two-dimensionally controlled microstructures in the range of micro- to nanometer sizes (1),(2),(3)(4). We have been developing a new technique to assemble micro-scale particles using the electric potential field (5), (6). This technique is principally based on electrophotography (7). The main procedure is composed of the following two steps: An electrified pattern is formed on a non-conductive substrate by the scanning of an electron or a Ga^+ ion beam(8). The substrate with the electrified pattern is then dipped into a suspension in which the particles are dispersed. Figure 1 shows a typical result for the arrangement of 5μm diameter silica spheres (SiO_2).

An electrified line on the substrate forms a non-uniform electric potential field. As a dielectric medium polarizes under the influence of an electric field, the particle is subjected to an electric gradient force. If the particle is charging, the particle is subjected to Coulomb's force from the potential field in addition to the gradient force. These forces are important in the arranging process. However, we have not discussed these forces in detail.

The purpose of this paper is to investigate the electrostatic force, which causes the migration of the particles in a suspension.

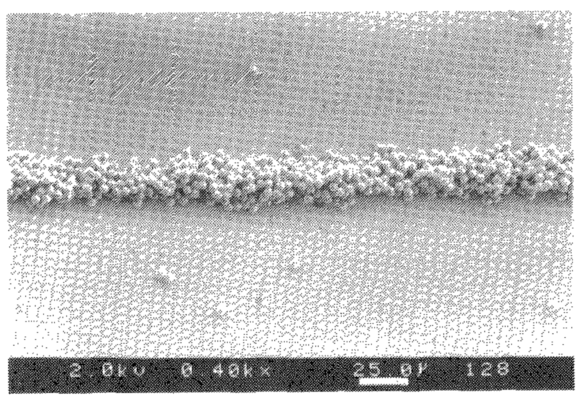

Figure 1. SEM image of the arrayed SiO_2 spheres on the $CaTiO_3$ substrate.

2. EXPERIMENTS

2.1 Assembling particles

Negatively electrified patterns were formed on $CaTiO_3$ substrates (Kyocera Co.,) by drawing with a focused electron beam (e^-) with a beam energy of 5keV. In contrast, positively electrified patterns were formed on substrates by drawing with a focused ion beam (Ga^+ ion) having a beam energy of 30keV. In this paper 5μm SiO_2 spheres (Ube-nitto Kasei Co.) were used. The SiO_2 spheres were homogeneously dispersed in a perfluorocarbon liquid (Fluorinerte FC-40, B.P.=155°C, Sumitomo 3M) by ultrasonic agitation. Fluorinerte FC-40 is a non-polar (low permittivity) and high resistive solvent. The suspension's particle concentration was 5×10^6 [counts/ml]. After drawing the electrified patterns, the substrates were dipped into the suspension at room temperature for 30 seconds. The substrates were immediately rinsed with a volatile liquid (Fluorinerte FC-72; B.P.=56°C) and then dried in air. The SiO_2 spheres arranged on the substrates were observed using a scanning electron microscope at 2keV. The electro-migrations of the SiO_2 spheres in FC-40 were investigated using a zeta potential meter with a non-polar solvent cell (ELS-8000, Otsuka Densi, Co.).

2.2 The electric field analysis

Space distribution of the electric field strength around the electrified line was calculated using the finite-element field-analysis software (Maxwell 3D, Ansoft Corp,). The general operating principle of the software is as follows: The solution space is divided into a tetrahedral mesh and the potential is calculated at each vertex and the mid-point of every side from Poisson's equation. The potential is approximated by a low-order polynominal so that the electric field across each tetrahedron can be calculated with the accuracy of the solution controlled by the number of elements in the mesh. The software performs an error analysis on the field in each tetrahedron and then refines the mesh where the error is the greatest, increasing the number of elements until the desired solution accuracy is reached.

For the calculation, an electrified line is supposed to be located on the surface of the $CaTiO_3$ substrate. The size of the line is 400μm in length, 1μm in width and 1μm in depth. The charge of the line is supposed to be 40[pC] and uniformly dispersed in the line. The electric field (E [V/m]) and ∇E^2 [V^2/m^2] were obtained by solving the Poisson equation. Variations in the Coulomb and gradient forces were calculated in the vertical direction from the surface of the substrate at the center of the electrified line.

3. RESULTS & DISCUSSION

3.1 Experimental approach

In the zeta potential measurement, the SiO_2 spheres migrated to the positive electrode in the FC-40 solvent. Consequently, the SiO_2 spheres were charged with a negative polarity.

Figure 2 shows a relationship between the electric field and terminal velocity of the SiO_2 sphere in the FC-40 solvent. It is clear that the velocity is proportional to the electric field. The slope of the line stands for the electrophoretic mobility (u [cm^2/Vs]) and its value is 1.8×10^{-6}. The ζ potential of the SiO_2 sphere can be calculated using the following Hückel equation [9].

$$u = (2/3)\varepsilon_1\varepsilon_0\zeta/\eta \quad (1)$$

where ε_1 is the relative dielectric constant of the FC-40 solvent (1.89[-]), ε_0 is the permittivity of a vacuum (8.854×10^{-12}[F/m]) and η is the viscosity of the FC-40 solvent (4.1×10^{-3}[Pa•s]). Substituting each value into eq.1, the ζ potential of the SiO_2 sphere is calculated to be -66mV. The average charge of the SiO_2 sphere (radius[r]: $2.5*10^{-6}$[m]) can be obtained from the following equation [9].

$$q = 4\pi r\eta\varepsilon_1\varepsilon_0\zeta \quad (2)$$

From eq.2, the average charge of the SiO_2 sphere is -3.5×10^{-17}[C] in the FC-40 solvent.

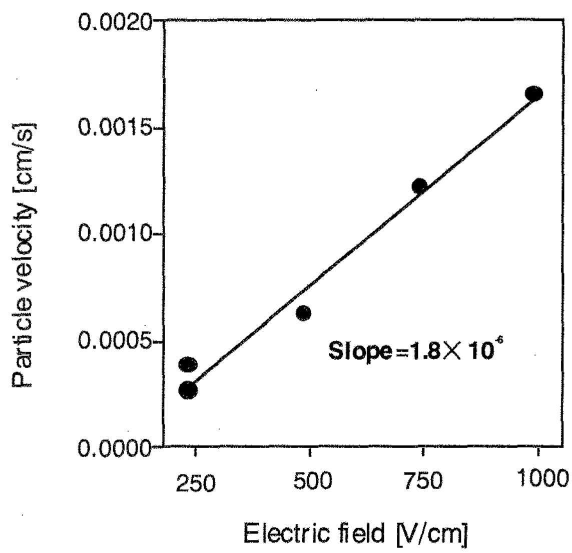

Figure 2. Relationship between the electric field and velocity of SiO_2 spheres in the FC-40 solvent.

The SiO_2 spheres in the FC-40 solvent were arrayed on both the negatively and positively electrified patterns [5),(6]. Figure 1 shows the SiO_2 spheres arrayed on the negatively charged line. In this case, the SiO_2 spheres are negatively charged and the line is also negatively charged. Therefore, Coulomb's force acts as a repulsive force. However, the particles were arrayed on the substrate as shown in Fig.1. This experimental result suggests that the gradient force (acting as an attraction force) is stronger than Coulomb's force (acting as a repulsion force).

3.2 Theoretical approach

Suppose that a SiO_2 sphere is placed near an electrified line on the $CaTiO_3$ substrate in the FC-40 solvent. The electrified line attracts the SiO_2 sphere by an electrostatic force (F), which is expressed by the following equation.

$$F = Fg \pm Fc \qquad (3)$$

The first and second terms on the right side of the equation represent the gradient force (Fg) and Coulomb's force (Fc), respectively. They can be expressed by the following equations [10].

$$Fc = qE \qquad (4)$$

$$Fg = 2\pi r^3 \varepsilon_1 [(\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + 2\varepsilon_1)] \nabla E^2 \qquad (5)$$

F_g always plays a role in the attractive force because the permittivity of the particle (ε_2=4) is greater than that of the solvent (ε_1=1.89). On the other hand, F_C is both attractive and repulsive, according to the polarity of the electrified line. The value of q, obtained from the electro-migration, is 3.5×10^{-17}[C]. E and ∇E^2 are calculated as a function of the distance from the electric field analysis. Therefore, both Fg and the Fc can be calculated as a function of the distance.

For a positively electrified line, the electrostatic force stands for F (▲) = Fg + Fc. On the other hand, the electrostatic force stands for F (▼) = Fg - Fc for a negatively electrified line. Figure 3 shows the calculated electrostatic forces to a negatively charged SiO_2 sphere, which is subjected to a positively or negatively electrified line near the surface of the substrates. The electrostatic forces become attractive force within 20μm from the surface, This theoretical result supports the experimental results that negatively charged SiO_2 spheres are arrayed on the negatively and positively electrified lines.

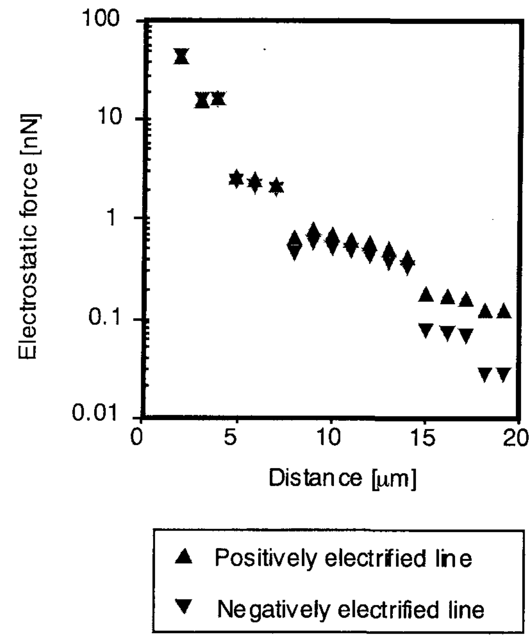

Figure 3. Electrostatic forces obtained by the numerical analysis for electric potential fields near the substrate.

4. CONCLUSION

The experimental and theoretical results conclude that the gradient force was stronger than Coulomb's force near the surface of the substrate. We believe that the non-uniform potential field plays an important role in the assembling process of the particles.

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