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Mechanics of a process to assemble microspheres on a patterned electrode

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A process has been demonstrated recently to assemble microspheres on a patterned electrode under the influence of an applied voltage. Here we examine the mechanics of this process, and describe both the conditions under which excess microspheres jump off the electrode when the voltage is applied, and the forces that attract the remaining microspheres to the desired positions. A quantitative mechanistic understanding of this process rationalizes experimental observations, provides scaling relations, and suggests modifications of the process. © 2006 American Institute of Physics. [DOI: 10.1063/1.2191743]

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sphere jumps away from the electrode when \( F_E > F_g \); this inequality gives the scaling relation for the minimum voltage,

\[
U_{\text{min}} \sim D \frac{d \rho g}{e_0}.
\]

Using representative values, \( \rho = 2.44 \times 10^3 \text{ kg/m}^3 \), \( d = 100 \mu\text{m} \), and \( D = 20 \text{ mm} \), Eq. (1) gives an order of magnitude estimate, \( U_{\text{min}} \sim 10 \text{ kV} \); this estimate is consistent with the experimental observation. Here we have ignored adhesion between the microspheres and gold film; both our study and previous studies\(^{10,11} \) have shown that adhesion only becomes important for spheres less than about 10 \( \mu\text{m} \) in diameter. This conclusion, however, may be altered by high humidities or patterned surfaces; we have not studied the effect of adhesion in this process.

We next consider the electrostatic forces that attract the remaining spheres to the windows. In a parallel-plate capacitor, the attraction between the two electrodes causes a Maxwell stress \( eE_0^2/2 \), where \( e \) is the permittivity of PS.\(^8 \) If the gold electrode were continuous and had no windows, the attractive force on a circular area of diameter \( d \) of the gold electrode would be \( F_0 = e(\pi d)^2/8 \). In the experimental setup, however, the gold electrode contains windows, each of which is covered by an equipotential glass sphere. The electric field inside the capacitor exerts an attractive force \( F \) on the sphere; this force \( F \) scales with \( F_0 \), but should be smaller than \( F_0 \) because of the curvature of a sphere, it can only partially cover the window. For a given location of a sphere, we first solve the electrostatic field by using the finite element method and then calculate the force \( F \) on the sphere by integrating the Maxwell stress. As an example of such a calculation, Fig. 3 shows that the attractive force is \( F = 0.7F_0 \) when the sphere is adjacent to the window and decays rapidly when the sphere is further above the window. Additional calculations for particles of other shapes and at locations away from the center axis of the windows also showed that the electrostatic force is attractive and localized around the windows. For representative values, \( U = 10 \text{ kV} \), \( t = 1 \text{ mm} \), \( d = 100 \mu\text{m} \), and \( e = 2.6e_0 \), we find that \( F_0 = 9.0 \mu\text{N} \). By comparison, the weight of such a glass sphere is \( F_g = 0.013 \mu\text{N} \). The electrostatic force attracts the sphere to the window; this force appears to be sufficient to overcome other forces such as friction that would prevent the sphere from moving laterally. A detailed study of this competition is beyond the scope of this Letter. Experimentally, we observed that the quality of assembly improved if we gently tapped the PS plate; this tapping presumably reduced the effects of friction and stickiness.

The mechanistic picture rationalizes various experimental observations. For example, as the applied voltage increased and spheres were ejected from the pile on the surface, the pile shrank from the periphery to the center of the gold film, indicating that the excess spheres at the periphery jumped away at a lower applied voltage than those at the center. This observation is consistent with the distribution of the electric field above the gold film: the electric field increases with the distance from the center of the gold film. In order to assemble spheres with a low rate of defects, our experiments also showed that the applied voltage must be within a certain range. If the applied voltage was too low, the fringe electric field above the gold film was insufficient to lift the spheres against gravity, as discussed above. If the applied voltage was too high, many windows in the gold film remained vacant, and did not house spheres. This observation could also be interpreted within our model. Upon applying a large voltage, the surface of the PS windows might become charged; this charging could be from either charge injection\(^{12} \) or air ionization and deposition\(^{13} \). Experimentally, we are able to visualize a corona at the corners of the gold electrode as well as observe the ionic breeze from the electrode when using the high voltages. These charges would shield the glass spheres on the windows from the electric field inside the capacitor, so that even these spheres could be lifted by the fringe electric field above the surface.

Our mechanistic picture also suggests improvements to the process. Equation (1) shows that the minimum voltage to lift spheres against gravity scales with the diameter \( D \) of the biased electrode. Consequently, to assemble spheres over a large area, we would need a very high voltage. To shorten the path of the voltage drop, we placed a second metal plate at a height \( H \) above the gold film, in addition to the metal support beneath the PS plate. We grounded the two metal plates and applied a voltage to the gold film. This arrangement of the electrodes was used to determine a minimum voltage for the excess spheres to jump off the gold film, but was not optimal for high-yield assemblies. With this geometry, the ejected spheres bounced off the upper electrode and returned to the original location. Thus, we were able to increase the yield of high-quality assemblies.

\[ U = \frac{D \rho g}{e_0} \]

When the spheres were ejected from the thin gold film, the area of the gold film \( A_g \) is typically several millimeters squared, whereas the area of the PS window \( A_w \) is typically several square centimeters. From Eq. (1), the minimum voltage for a PS window \( U_{\text{min}} \) is roughly three orders of magnitude above the voltage for a gold film \( U \). This result is consistent with our experiments.
and length measures the effective voltage path in a given design. This allows for the arguments leading to Eq. (1) now give $U_{\text{min}} = \lambda \cdot d \cdot g / e_0$, where $\lambda$ is a length that measures the effective voltage path in a given design. This length $\lambda$ depends on the geometry of the electrodes, but is independent of the size and the material of the spheres, provided they are charged to the potential of the gold film. When spheres of different sizes and materials are assembled using the same configuration of the electrodes, the ratio of the minimum voltages required to lift the excess spheres is $U_{\text{min}} / U_{\min} = (\rho \cdot d) / (\rho \cdot d)$. Observe that this ratio is independent of the geometry of the electrodes. Taking $\rho_{\text{glass}} = 2.44 \times 10^3$ kg/m$^3$, $d_{\text{glass}} = 75 \mu$m, $\rho_{\text{Cu}} = 8.92 \times 10^3$ kg/m$^3$, and $d_{\text{Cu}} = 30 \mu$m, we obtain a theoretical value $U_{\text{Cu}} / U_{\text{glass}} = 1.21$, which is in good agreement with the experimental values listed in Table I. This agreement between the minimum electric fields for different diameters of the biased electrode lends support to the two major assumptions in our model: the lifting condition is governed by the competition between the electrostatic and gravitational forces with negligible effect of adhesion, and the glass spheres are charged to the same electric potential as the gold electrode.

In summary, we have shown that the process developed by Winkleman et al. requires two electric fields: the field above the gold film $E_1$ to lift excess spheres against gravity and the field below the gold film $E_2$ to attract the spheres to the windows. Our scaling relation for the minimum voltage is consistent with the experimental data of both original and modified geometries of electrodes. This mechanistic understanding enables us to modify the process in many other ways to fulfill various design requirements and reinforces the notion that the electrostatic forces can rapidly assemble small objects over large areas.

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Table I. Experimental values of the minimum voltage to lift the excess spheres. A third electrode was placed distance $H$ above the gold film.

<table>
<thead>
<tr>
<th>$H$ (mm)</th>
<th>$U_{\text{glass}}^{\text{min}}$ (kV)</th>
<th>$U_{\text{Cu}}^{\text{min}}$ (kV)</th>
<th>$U_{\text{Cu}}^{\text{min}} / U_{\text{glass}}^{\text{min}}$</th>
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