Dielectric particle lofting from dielectric substrate exposed to low-energy electron beam

P V Krainov\textsuperscript{1,2,5}, V V Ivanov\textsuperscript{1}, D I Astakhov\textsuperscript{1,3}, V V Medvedev\textsuperscript{1,2}, V V Kvon\textsuperscript{4}, A M Yakunin\textsuperscript{4} and M A van de Kerkhof\textsuperscript{4}

\textsuperscript{1} Institute for Spectroscopy of the Russian Academy of Sciences, Fizicheskaya str. 5, Troitsk, Moscow 108840, Russia
\textsuperscript{2} Moscow Institute of Physics and Technology, Institutsky pereulok str. 9, Dolgoprudny, Moscow region 141701, Russia
\textsuperscript{3} ISTEQ B.V, High Tech Campus 9, 5656 AE Eindhoven, The Netherlands
\textsuperscript{4} ASML Netherlands B.V, De Run 6501, 5504DR Veldhoven, The Netherlands

E-mail: pavel.krainov@phystech.edu

Received 27 January 2020, revised 8 July 2020
Accepted for publication 13 July 2020
Published 18 August 2020

Abstract
The particle-in-cell simulation is applied to study a nanometer-sized dielectric particle lofting from a dielectric substrate exposed to a low-energy electron beam. The article discusses the electron accumulation between a substrate and a particle lying on it, which can cause the particle lofting. The results are of interest for dust mitigation in the semiconductor industry, the lunar exploration, and the explanation of the dust levitation.

Keywords: dust lofting, electron beam, plasma sheath, dust transport in plasma

( Some figures may appear in colour only in the online journal)

1. Introduction

Extreme ultraviolet lithography (EUVL) is a technology for integrated circuits (IC) manufacturing \cite{1}. This technology uses EUV light of a 13.5 nm wavelength to transfer a pattern from a photomask (also called a reticle) to a light-sensitive photoresist on a wafer \cite{2}. In view of the IC feature sizes of $<20\,\text{nm}$, any particles on the surface of a reticle of $>20\,\text{nm}$ can cause defective patterns to be printed \cite{3}. Therefore, release and transport control of these nanoparticles is vitally important for EUVL \cite{4}.

The process of EUVL \cite{5} occurs in a low-pressure hydrogen atmosphere to prevent oxidation of mirrors and carbon growth. The absorption of EUV radiation results in the formation of EUV induced hydrogen plasma. It consists of two parts: fast photoelectrons ($E \sim 70\,\text{eV}$) and a bulk plasma ($n_e \sim 10^8\,\text{cm}^{-3}$, $T_e \sim 0.5\,\text{eV}$). Both fast electrons and plasma charge surfaces they can reach. It has been reported in several experiments \cite{6–8} that a plasma and an electron beam with similar parameters can lift off dust particles from surfaces.

In 1992, Sheridan \textit{et al} \cite{6} observed the shedding of the dielectric dust from an aluminum sphere covered by an oxide layer and simultaneously exposed to a plasma and an electron beam. According to the reported hypothesis, which was expanded later \cite{9}, a particle is charged by the plasma and lifted by the electric field of the plasma sheath. In 2006, Flanagan and Goree \cite{7} repeated Sheridan’s experiment for a glass sphere covered with regolith and detected the same dust shedding. Wang \textit{et al} \cite{8} investigated the lofting from a heap of regolith particles under the influence of a plasma, an electron beam, their combination, and UV radiation. In accordance with the developed ‘patched charge model’, electrons penetrate into cavities between particles, charge their hidden surfaces with the help of secondary electron emission, and cause the release. All of the aforementioned authors noted the key importance of an electron beam addition in a plasma for the lofting phenomenon.
The core objective of this article is to show a new mechanism of a single particle lofting from a surface. Here we deal with a single dielectric particle resting on a dielectric substrate exposed to a low-energy electron flux, without a plasma or high-energy EUV photons. By kinetic numerical simulation, we demonstrate the accumulation of electrons between a particle and a substrate (figure 2), which leads to the occurrence of a high repulsive force during charging transient. Besides, we give the consistent description of particle charging, including dielectric polarization, which leads to the occurrence of a mirror force. This force has not been considered in the literature, to the best of our knowledge.

2. Model and geometry

The process of a particle and a substrate charging was simulated by means of the two-dimensional ($r$-$z$ axial symmetry) model [10] based on a particle-in-cell method [11]. The main loop of the method consists of a Poisson equation solver, which is followed by updating the charged particles positions and velocities based on the obtained field distribution and current particles velocities. The model was developed for the simulation of EUV induced plasma and was validated in several experiments [12–14].

The lower part of the simulation domain was filled by a dielectric substrate (2 μm). A spherical dielectric particle (100 nm) was placed $z = 1$ nm above the substrate to effectively account for some roughness of the particle and the substrate surfaces. But the shape of both particle and substrate was smooth before projection on a grid, otherwise too dense a grid was needed to resolve all the details. It was assumed that the particle and the substrate were made of silicon dioxide.

The substrate was exposed to a spatially and temporally uniform flux of 70 eV electrons flux $\Phi = 10^{12}$ cm$^{-2}$s$^{-1}$. A vertical incidence of electrons was implemented in order to exclude the contribution of primary electrons and focus on the accumulation of secondary electrons under the particle. No external electric field was applied due to the same reason: to focus on the repulsion caused by the accumulation of secondary electrons.

The simulation domain boundaries were placed more than several micrometers away from the particle. The potential of a charged particle equals to about zero at such a distance. It enables one to use the simplest boundary condition to solve the Poisson equation: grounded electrode. In addition, such remoteness of the boundaries enabled to neglect the interaction of the charged particle with its images in the boundaries. Non-uniform rectangular grid was exploited to solve the Poisson equation. A cell size in the place of the particle location was 1 nm.

In the simulations, the dielectric was assumed to be an ideal insulator. Dielectric cells accumulated charges and kept them up to the end of the simulation. The dielectric could be polarized according to the corresponding dielectric permittivity ($\varepsilon$SiO$_2$) $\approx 3.9$.

The electron backscattering and the secondary electron emission (SEE) induced by electrons were taken into consideration. Both processes were merged into one process of SEE due to the lack of experimental data, which did not allow separating those processes entirely. The characteristics of SEE included spectrum [15], angular distribution [16], and total secondary electron emission yield (SEY). The latter shown in figure 1 consists of inelastic backscattering [17] and ‘true’ secondary emission [18, 19]. The term ‘first crossover energy’ $E_{c1}$ is the key term for understanding processes described below: $\text{SEY}(E_{c1}) = 1$. $E_{c1} \approx 44$ eV for SiO2. Finally, it should be noted that every emitted secondary electron was treated in the model as a primary electron, i.e., it participated in all the electron processes mentioned above.

3. Forces

The bombardment of a flat dielectric substrate by 70 eV electrons leads to its positive charging, because released secondary electrons leave it freely and secondary emission yield $\text{SEY}(70 \text{ eV}) > 1$. In other words, the current of secondary electrons from the substrate is larger than the current of primary electrons to the substrate, i.e., the total current to the substrate is positive. The temperature of secondary electrons $T_{sec} \approx 3 \text{ eV}$ [15]. Hence, in the stationary state, the substrate acquires a low potential $\phi \sim +1 \text{ V}$, which returns back part of secondary electrons and leads to effective $\text{SEY} = 1$.

Some of the secondary electrons released next to the particle hit it, then experience either absorption, or backscattering, or release new secondary electrons. Backscattered and new secondary electrons, in their turn, hit the substrate under the particle, undergoing the same process again and again. The described process leads to the accumulation of electrons locally on the particle surface and on the surface of the substrate under the particle as shown in figure 2.

The accumulation of electrons under the particle results in an extra repulsive force $F_e$ (figure 2) caused by Coulomb repulsion between electrons. Besides, there are four more forces acting on the particle (figure 2).

In general, the particle might be influenced by an external electric field $E$. It might be a field of plasma sheath or a specially applied external field. Force $F_e$ is the action of the field $E$ on the total particle charge $Q_p$.

\[
F_e = Q_p E. \tag{1}
\]
An electrical image forms in a dielectric for any charge above it due to dielectric polarization ability, and attracts the charge. For instance, a point-like charge \( q \) placed in vacuum at the distance \( L \) from a flat dielectric with permittivity \( \varepsilon \) experiences the attraction to the surface with a force

\[
F_{\text{inc point-like}} = \frac{1}{4\pi\varepsilon_0}\frac{\varepsilon - 1}{\varepsilon + 1} \frac{q^2}{(2L)^2},
\]

where \( \varepsilon_0 \) is the vacuum permittivity. Thus, the particle is attracted to the substrate with the mirror force \( F_{\text{inc}} \). It includes the interaction of charges on the particle with their images in the dielectric substrate and vice versa.

The van der Waals force is usually considered as an adhesive force \( F_{\text{adh}} \) in vacuum. The attraction between a smooth spherical particle and a smooth plane can be found with the Hamaker formula

\[
F_{\text{adh}} = F_{\text{vdW}} = \frac{A_{\text{Ham}} R}{6 \varepsilon_0} \approx 6 \text{ nN},
\]

where \( R \) is the particle radius (50 nm), \( A_{\text{Ham}} \) — the Hamaker constant \((66 \times 10^{-21} \text{ J})\) for SiO\(_2\) [20]). We substituted the minimum possible separation distance \( z = 0.3 \text{ nm} \) (intermolecular distance) between the particle and the substrate to obtain the upper estimation. In practice, the van der Waals force is 1–2 orders lower because of surface asperities and/or adsorbates [21].

The gravitational force also acts on the particle.

\[
F_g = \rho V g \approx 10^{-17} \text{ N},
\]

where \( \rho \) is the particle density (2.5 g cm\(^{-3}\) for SiO\(_2\)), \( V \) is the particle volume, and \( g \) is the gravitational field (10 m s\(^{-2}\)). In general, the substrate can be arbitrarily oriented. Consequently, the gravitational force can have an arbitrary direction.

The total force acting on the particle

\[
F_t = F_e + F_C - F_{\text{inc}} - F_{\text{adh}} - F_g.
\]

According to the reason discussed in section 2, no external electric field was applied. Therefore, \( F_e \) can be removed from this equation. Besides, the gravitational force is several orders lower than the considered adhesive force \( F_g \ll F_{\text{adh}} \). To sum up, the total force acting on the particle consists of three components in our problem

\[
F_t = F_C - F_{\text{inc}} - F_{\text{adh}} = F_{\text{eff}},
\]

where \( F_{\text{eff}} \) denotes the total electric force.

4. Results

In the simulation, the substrate and the particle resting on it are exposed to the flux of primary electrons. Besides, the particle experiences the bombardment by secondary electrons released from the substrate. The obtained potential and charge distributions are shown in figure 3. On the surface of the substrate far from the particle, a low positive charge density is formed in the same way as it does in the case without a particle (see section 3). In the very first stage, the area with the highest negative charge density (and highest negative potential) forms on the lower part of the particle (figure 3(a)). Also, a non-uniformly charged spot forms under the particle. As it follows from the analysis of the simulation results, positive bound charges prevail over the accumulated electrons in the center of the spot, i.e., right under the particle. And vice versa, the accumulated electrons prevail over the positive bound charges on the periphery of the spot. Both these results confirm the accumulation hypothesis sketched in figure 2. The size of the spot increases from \( r \approx R \) to \( r \approx 2R \) with time (\( R \) is the particle radius). Positive bound charges are caused by the polarization of the dielectric substrate by the negatively charged particle. Also, the analysis of the simulation results showed that the bound charges are mainly induced on the surfaces, but not inside the objects.

In the interpretation below, we keep track of following charges: the particle charge \( Q_{\text{pr}} \), the positive bound charge under the particle \( Q_{\text{bd}} \), and the accumulated negative charge on the substrate \( Q_{\text{sd}} \). We chose the spot with the mean size \( r_c = 1.5R \) to integrate these charges inside it. Figure 4 represents the total charge inside the spot \( Q_{\text{st}} = Q_{\text{sd}} + Q_{\text{bd}} \), figure 5 represents the dynamics of other introduced charges.

We divide the dynamics of the particle and the spot charged plotted in figures 4 and 5 into three periods. The first is the accumulation period (figure 4: 0–75 s, figure 3(a)). During the accumulation period, the lower part of the particle and the part of the substrate below the particle are negatively charged by low energy secondary electrons \((T_{\text{se}} \sim 3 \text{ eV})\) released from the substrate. Secondary emission yield \( \text{SEY}(E_{\text{sec}}) < 1 \) (figure 1) for such electrons, which makes a negative charging possible. At the same time, the upper part of the particle is exposed to energetic primary electrons and is charged up to a low positive charge density by them, because \( \text{SEY}(E_{\text{pr}}) \approx 1 \). But some points of the upper part can be charged negatively by primary electrons because of particle surface roughness. Asperities absorb part of secondary electrons and effectively reduce \( \text{SEY}(E_{\text{pr}}) \). The roughness is caused by the projection of the particle on the rectilinear grid. Besides, the region of the
Figure 3. Simulated potential and charge distribution (includes both free and bound charge) over a dielectric particle and a dielectric substrate exposed to a 70 eV electron flux. The black dash-dotted lines denote surfaces of the substrate and the particle. The red dashed curves are equipotential surfaces. A non-uniformly charged spot forms on the substrate under the particle. The negative part is caused by electron accumulation (figure 2 states). The positive part right under the particle is caused by the polarization of the dielectric substrate by the negatively charged particle. (a) Integrated negative spot forms on the substrate under the particle, because of accumulation of secondary electrons (figure 2). It leads to the occurrence of a repulsive force (figure 4). (b) Upper part of the particle is hit by slowed down primary electrons: $E_{\text{pr}}' \approx 70 \text{ eV} - 26 \text{ eV} = 44 \text{ eV} \leq E_{\text{crit}}$. $\text{SEY}(E_{\text{pr}}') \leq 1$. The upper part starts intense charging. (c) Particle is approximately uniformly charged because of the previous intense charging of the upper part. (d) Charge density and potential reach their maximum values on the upper part of the particle, leading to attraction due to the mirror force (figure 4).

Figure 4. Total electric force ($F_{\text{tot}} = F_{C} - F_{\text{mc}}$) acting on the particle and the total charge $Q_{st}$ inside the spot on the substrate ($r_{s} = 1.5R$). The positive force is repulsive, the negative force is attractive. The accumulation period: the growth of the repulsion force $F_{C}$ due to the electron accumulation under the particle; the direct charging period: the fast charging of the upper part of the particle by primary electrons causes the growth of the positive bound charge inside the spot and the rise of the mirror force $F_{\text{mc}}$; the saturation period: slowly continued electron accumulation under the particle.

Figure 5. Charges of the interacting objects: the particle and the spot on the substrate ($r_{s} = 1.5R$).

This rise leads to the deceleration of primary electrons hitting the particle.

At the moment 75 s the potential of the upper part of the particle becomes equal to $\phi_{\text{upper part}} \approx -26 \text{ V}$ (figure 3(b)). Primary electrons, which hit the upper part, are slowed down to $E_{\text{pr}}' \approx 70 \text{ eV} - 26 \text{ eV} = 44 \text{ eV} \leq E_{\text{crit}}$. The primary electrons cease to charge the upper part of the particle positively, its negative charging begins ($\text{SEY}(E_{\text{pr}}') \leq 1$). For this reason, the total negative charge of the particle $Q_{p}$ begins to grow faster starting from $t = 75 \text{ s}$ (see figure 5). This qualitative change in
the process of the particle charging opens the direct charging period (figure 4: 75–150 s).

During the direct charging period, the lower part of the particle is slowly charged by secondary electrons from the ‘tail’ of the spectrum. Whereas the upper part is directly charged by the intense flux of decelerated primary electrons. The latter process is the main in this period and substantiates its name. Thus, the upper part is charged faster than the lower part. This causes relocation of the highest negative potential from the lower part of the particle to its upper part (figures 3(c) and (d)). The acceleration of the particle charge \( Q_p \) growth, in its turn, leads to a faster rise of the positive bound charge under the particle \( Q_{sb} \). Moreover, the bound charge begins to rise faster than the negative free charge \( Q_{sf} \). That is why the flip in the dynamics of the total spot charge \( Q_{st} \) is observed during the direct charging period (figure 4). In other words, the described accumulation of electrons under the particle acts as a trigger for the upper part of the particle. It charges positively first, and after the trigger charges negatively. Such a trigger mechanism is responsible for the flip of the total charge of the substrate surface within the considered spot \( Q_{st} \) (figure 4).

During the saturation period (figure 5: > 150 s), the particle charge remains stable, because the particle reflects or scatters incident primary and secondary electrons. Residual charging of the spot on the substrate takes place until its potential becomes equal to the maximum energy of secondary electrons \( E_{sec, max} \approx 60 \text{ V} \) [15].

The rest of the section is dedicated to the analysis of the total electric force \( F_{ref} \) acting on the particle (figure 4). The force was calculated as integral over the particle:

\[
F_{ref} = F_C - F_{mc} = \int_{\text{particle}} E_z \, dq,
\]

where \( dq \) is the charge accumulated in a dielectric cell, \( E_z \) is \( z \) component (normal to the substrate) of the electric field in the same dielectric cell. The electric field was calculated from the potential distribution obtained as an output from the PIC model. The total force includes two parts: the attractive mirror force \( F_{mc} \) and the Coulomb repulsion \( F_C \). The third force \( F_e \) can be neglected because no external electric field was applied. Also, the potential difference formed during the simulation between the substrate surface and the upper boundary does not exert a significant force \( F_e \). The volume charge did not form in the simulation domain because of the weak electron flux and the small size of the domain.

The total electric force \( F_{ref} \) (figure 4) has a transient nature, because different parts of the particle are charged at various rates by different kinds of electrons (primary or secondary). But the dynamics of \( F_{ref} \) follows the dynamics of the total spot charge \( Q_{st} \), as it can be concluded from figure 4. During the accumulation period (figure 3(a)), the charge density reaches its maximum value on the lower part of the particle. Free and bound charges of the spot are comparable (figure 5: \( |Q_{sf}| \sim |Q_{sb}| \sim 500 \text{ e} \), but the spot is charged negatively in total (figure 4: \( Q_{st} \sim -100 \text{ e} \)). The interaction between the negatively charged lower part of the particle and the negatively charged spot leads to the occurrence of a strong repulsive force. Consequently, the rise of the total spot charge \( Q_{st} \) during the accumulation period causes the rise of the total electric force \( F_{ref} \).

During the direct charging period (figure 4: 75–150 s), the intense negative charging of the upper part of the particle takes place. It leads to an increase of the positive bound charge \( Q_{sb} \) on the substrate and an decrease of the total spot charge \( Q_{st} \). The mirror force acting on the particle \( F_{mc} \) grows. The total electric force changes its sign after about 110 s, i.e., becomes attractive. It means that the mirror force \( F_{mc} \) exceeds the repulsive Coulomb force \( F_C \). It is directly related to the aforementioned trigger mechanism. The mechanism is responsible for the flip and the transient nature of the total electric force.

In the saturation period (figure 4: >150 s), the force continues to grow slowly due to a slow charging of the spot on the substrate.

5. Discussion

First of all, let us compare the repulsive total electric force acting on the particle with the van der Waals force. The electric force takes its maximum value equal to about 7 nN during the accumulation period. This value is approximately equal to the upper estimation of the van der Waals force given in section 3. But we noted that in practice the van der Waals force is 1–2 orders lower, because of the surface asperities and/or adsorbrates. Therefore, the described above accumulation of negative charges on and under the particle can lead to itslofting from the surface under the considered conditions.

However, it is important to evaluate how the total electric and the van der Waals forces change as the particle moves away from the substrate. This information is shown in figure 6. The dependence of the van der Waals force on the separation distance includes only the interaction of the main bodies (a smooth spherical particle and a flat substrate) given by equation (3). It is presented by the dash-dotted blue line in figure 6. The surfaces roughness does not change the monotony of this dependence [22]. That is why this dependence is sufficient for our analysis. The electric force acting on the particle was calculated using our PIC code for several distances up to 300 nm. These calculations were carried out under the assumption that the distribution of the absorbed electrons on the surfaces of the particle and the substrate remains unchanged (constant). This assumption is substantiated in appendix A. We also took into account that the distribution of the positive bound charges changes with the increasing distance due to the changing polarization action of the particle on the substrate. The results of these calculations are shown with red dots in figure 6. The good approximation of such dependency for small separation distances is the interaction between a point-like charge and an uniformly charged disk (cyan dashed line in figure 6). For distances exceeding 300 nm, the repulsive force dependency merges with the Coulomb interaction between two point-like charges (red dashed line in figure 6). The formulas for both approximations are given in appendix B. In total, figure 6 shows that the van der Waals force is a short-range force in comparison with the total electric force. It can be concluded from this finding that
the particle jumps as soon as the sufficient amount of electrons was accumulated.

An electron accumulation mechanism can take place when a particle located on a substrate is subjected to a simultaneous action of a plasma and an electron beam. In this case, an additional electric force $F_e = Q_eE$ pulls the particle away from the host surface. Here $E$ is the electric field of the plasma sheath. Its magnitude can reach $10^5$ V m$^{-1}$ [5]. Suppose that in the numerical experiment considered above such a force acts on the particle. For $E = 10^5$ V m$^{-1}$ and $Q_e = -1000e$, we obtain $F_e = 0.02$ nN (green dotted line in figure 6). This force is about two orders of magnitude lower than the attractive van der Waals force and the repulsive force caused by accumulated electrons. Unlike the latter force, $F_e$ does not depend on the distance between the particle and the substrate, because the plasma sheath thickness (about 1 mm) is much larger than the particle size. The above mentioned particle jump results in a significant reduction of the adhesion. The van der Waals force becomes less than the additional force $F_e$. Hence, the electric force $F_e$ enables the removal of the lofted particle at a large distance for the host surface.

To finish the discussion of the conducted numerical experiment, we analyze the validity of the chosen 2D $r$–$z$ simulation approach. Unlike a hypothetical 3D model, a 2D $r$–$z$ model cannot take interaction between single point-like charges into account in the right way, because a single point-like charge is represented in the model as a ring around the axis of symmetry. Nevertheless, the dielectric particle received more than 1000 electrons during its charging as figure 5 demonstrates. These electrons should be uniformly distributed around the symmetry axis of a particle, because of the axial symmetry of the problem. Therefore, the 2D model should provide the same value of the electric force as a hypothetical 3D model.

Now let us turn to the comparison of the simulation results with other relevant studies. Wang et al [8] observed the particle release from a heap of regolith particles under the exposure of a 120 eV electron beam. To interpret the experiment, the authors developed a simple analytical model called ‘patched charge model.’ The model describes an equilibrium charge distribution over a particle. According to the model, the particle top surface is directly charged by an electron beam or a plasma. The rest of the particle surface comprises boundaries of inter-particle microcavities and is charged by secondary electrons to a much greater charge. Thereby, this equilibrium state can be characterized by the equilibrium potential of the lower part of the particle. The latter is determined by the temperature of the secondary electrons $T_{se}$ ($\sim 3$ eV) and the empirical factor $\eta$ (7.3 for 120 eV electron beam [8]):

$$\phi_e = -\eta T_{se}/e. \quad (8)$$

The particle charge:

$$Q_e = 0.5C\phi_e, \quad (9)$$

where $C = 4\pi\varepsilon_0R$ is the capacitance of an isolated spherical particle.

Considered in the ‘patched charge model’ particle–particle configuration is similar to the particle-surface configuration we discuss. In addition, the charge distribution over the particle in the accumulation period of our simulation is similar to the predicted equilibrium state. Let us apply the ‘patched charge model’ to the numerical experiment considered in this paper. The equilibrium potential and charge of a 100 nm silica particle are $\phi_e \approx -22$ V and $Q_e \approx -400$ e. In the simulation, the lower part of the particle reaches this equilibrium potential at about 40 s, but its total charge equals to approximately $-600$ e at this moment. Also, we found that particle charging continues and charging of the top particle surface occurs. Such a difference in charging can be explained by different surface configurations or by different energy of incident electrons. As it comes from the above reasoning, a much higher accumulated charge and, therefore, more time are required for the top particle surface to be directly charged in case of exposure to the 120 eV electron flux.

Schwan et al [23] measured the buildup of electrons on a few microns silica particles loaded into a crater and exposed to a 120 eV electron beam. The distribution of the measured charges demonstrated the good agreement between the distribution peak and the prediction of the ‘patched charge model’. Besides, the authors detected a ‘tail’ in the distribution: particles with a charge several times higher (up to 4–5) than the predicted equilibrium charge. This broad charge distribution was explained by the broad size distribution of the particles. Here we would like to suggest another possible reason based on our numerical experiment. The particles could experience the process of intense charging of the top surface described in the direct charging period. In our numerical experiment, the particle finally received charge about $\approx -1800$ e. This charge is 4.5 times higher than the value predicted by the ‘patched charge model’ ($-400$ e). This enhancement coefficient is in agreement with the experimental value (4–5).

Figure 6. Reduction of forces acting on the particle with the particle-substrate separation distance. The charge distribution on the particle corresponds to the maximum value of the total electric force $F_{te}$ (75 s in figure 4). The van der Waals force includes the interaction between main bodies (a smooth particle and a flat substrate). The point-disk approximation of $F_{te}$ considers the particle and the spot as a point and a disk, respectively. The point–point approximation considers the particle and the spot as point-like charges. The formulas are given in appendix B. Force $F_e = Q_eE$ in an external electric field ($E = 10^5$ V m$^{-1}$) is also given.
It was concluded from two experiments [6, 7], that particle lofting occurs due to a fluctuating quantity. This conclusion seems to contradict the hypothesis of electron accumulation. The possible solution is following. If we overestimated the van der Waals force (notably, the same assumption was made previously by Sheridan et al [9]), a much lower charge need to be accumulated to overcome the adhesion. The charge can be about several tens of electrons (versus several hundreds in the current numerical experiment). In such a case, the repulsive force between the particle and the spot on the substrate highly depends on the mutual disposition of the accumulated electrons. This disposition is determined by the stochastic and discrete nature of arriving electrons. The dependence on mutual disposition can be a source of repulsive force fluctuations at the early stage of electron accumulation. Unfortunately, this effect cannot be captured by our 2D PIC model as it averages charge distributions on dielectric surfaces over the polar angle.

The main candidate proposed in the literature [6, 7, 9, 24] to be the fluctuating quantity is the total charge of a dust particle $Q_p$ that fluctuates to a large negative value in spite of the low average value. Force $F_e = Q_p \times E$ was supposed to be responsible for the particle lofting. At the same time, it was noted [7–9] that the estimations of force $F_e$ give insufficient value to overcome the van der Waals force. But another proposal about the fluctuating quantity was made [6, 7]: a binary Coulomb repulsion between two neighboring or touching dust particles with fluctuating charges. This proposal corresponds to our hypothesis about the fluctuating interaction in the early stages between the particle and the spot on the substrate.

To summarize, let us formulate a new mechanism of particle lofting based on the conducted simulation. The mechanism consists of two stages. In the first stage, the electron accumulation between the particle and the substrate occurs. The negatively charged spot forms on the substrate under the particle. The repulsive interaction between the particle and the spot causes a particle jump. This interaction can be fluctuating at the early stage of accumulation. It is worth noting that the electron accumulation occurs regardless of any global electric field presence. The jump results in a significant reduction of the attractive van der Waals force. In the second stage, if a sufficient electric field (in plasma sheath or specially applied) presents, the electric field drives the following particle movement. It can carry the particle through the sheath to the bulk plasma.

The above analysis focused on dielectrics, but the described principles can also be applied to most metals. Metals typically have a surface oxide layer of several nm thickness, which can make the electron accumulation described above possible.

### 6. Conclusion

The article demonstrated a new mechanism of a dielectric particle lofting from a dielectric substrate exposed to a low-energy electron beam. By the particle-in-cell simulation, the charging transient of the particle was investigated. We revealed the effect of considerable electron accumulation between such a particle and a substrate, leading to the occurrence of a strong repulsive force acting on the particle. The charge particle received during the accumulation is in agreement with the recently developed ‘patched charge model’ and conducted experiments. The accumulation is followed by a rise of the total particle charge that causes the particle attraction to the substrate due to an increased mirror force. The repulsive force as obtained in the simulation can exceed an attractive adhesive force. This repulsive force reduces slower with the particle–substrate separation distance than the adhesive force. It results in particle lofting as soon as a sufficient amount of electrons is accumulated.

### Appendix A Clarification of the calculation of figure 6

An implicit assumption was used to calculate the red dots in figure 6: the particle charge distribution does not change during its lofting. The assumption can be supported by the following evaluations. The time between two subsequent electron–particle collision is

$$\tau_e = (\text{flux} \pi R^2)^{-1} \approx 6 \text{ ms}. \quad (A1)$$

To estimate a typical time of lofting accept the particle diameter as characteristic length and value of the van der Waals force as a characteristic force, then:

$$\tau_t = \sqrt{\frac{2R}{F_{vdw}/m}} \approx 10 \text{ ns} \ll \tau_e \approx 6 \text{ ms}. \quad (A2)$$

It is worth noting that a close value (1 ns) for particle lofting was estimated previously [24].

### Appendix B Approximations of the total electric force dependency on the separation distance

The dependency on the separation distance ($z$) of the total electric force ($F_{tot}$) acting on the particle ($R$ is the particle radius) is shown in figure 6. Here we provide approximations of this dependency for small and large separation distances.

For small distances $z \ll R$, the spot on the substrate is considered as a uniformly charged disk. The charged particle is considered as a point-like charge placed in the particle center, because most of accumulated charges is situated near the particle equator (figure 3(b)). The electric field on the axis of symmetry of a uniformly charged disk is given by

$$E_{\text{disk}}(z) = \frac{1}{2\varepsilon_0 \pi r_d^2} \left(1 - \frac{z}{\sqrt{r_d^2 + z^2}}\right). \quad (B1)$$

where $Q_d$ is the disk charge, $r_d$ is the disk radius. Substituting $z + R$ as $z$, the total spot charge $Q_s$ as the disk charge $Q_d$, the spot radius $r_s = 1.5R$ as the disk radius $r_d$ in equation (B1) and multiplying by the total particle charge $Q_p$, we have the approximation.

For large distances $z \gg R$, the particle and the spot on the substrate can be considered as point-like charges. The
interaction between them can be found as

\[
F_{\text{point-point}} = \frac{1}{4\pi\varepsilon_0} \frac{Q_{st} Q_{sf}}{z^2} - \frac{1}{4\pi\varepsilon_0} \frac{\varepsilon - 1}{\varepsilon + 1 (2c)^2} Q_{sf}^2 \quad (B2)
\]

The first term is the Coulomb repulsion between the spot and the particle, the second term is the mirror force between the particle and its image in the dielectric substrate with permittivity \( \varepsilon \).

It should be noted that the bound charges on the substrate surface are taken into account in different ways. In the point-disk approximation, the bound charges are included in the total spot charge \( Q_{st} \). In the point–point approximation, only the accumulated charge in the spot \( Q_{sf} \) is used, the bound charges are included implicitly in the second term.

**ORCID iDs**

P V Krainov \( \text{https://orcid.org/0000-0003-2094-9478} \)

**References**

[1] van de Kerkhof M A, Benschop J P H and Banine V Y 2019 Solid-state electronics selected papers from the future trends in microelectronics (FTM-2018) Workshop 155 20
[2] Wagner C and Harned N 2010 Nat. Photon. 4 24
[3] Scaccabarozzi L, Lammers N A, Moors R and Banine V 2009 J. Adhes. Sci. Technol. 23 1603
[4] Lercel M, Smeets C, van der Kerkhof M, Chen A, van Empel T and Banine V 2019 Photomask Technology 2019 vol 11148 (Bellingham: SPIE Optical Engineering Press) 111480Y
[5] Beckers J, van de Ven T, van der Horst R, Astakhov D and Banine V 2019 Appl. Sci. 9 2827
[6] Sheridan T E, Goree J, Chiu Y T, Rainder R L and Kiessling J A 1992 J. Geophys. Res.: Space Phys. 97 2935
[7] Flanagan T M and Goree J 2006 Phys. Plasmas 13 123504
[8] Wang X, Schwab J, Hsu H-W, Grün E and Horányi M 2016 Geophys. Res. Lett. 43 6103
[9] Sheridan T E and Hayes A 2011 Appl. Phys. Lett. 98 091501
[10] Astakhov D 2016 Numerical study of extreme-ultra-violet generated plasmas in hydrogen Ph.D Thesis University of Twente, Enschede
[11] Birdsall C K and Langdon A B 1991 Plasma Physics via Computer Simulation (Series in Plasma Physics) (London: Taylor and Francis)
[12] Astakhov D I, Goedheer W J, Lee C J, Ivanov V V, Krivtsun V M, Zotovich A I, Zyranyov S M, Lopaev D V and Bijkerk F 2015 Plasma Sources Sci. Technol. 24 055018
[13] Astakhov D I et al 2016 J. Phys. D: Appl. Phys. 49 295204
[14] Abrikosov A, Reshetnyak V, Astakhov D, Dolgov A, Yakushov O, Lopaev D and Krivtsum V 2017 Plasma Sources Sci. Technol. 26 045018
[15] Schreiber E and Fitting H J 2002 J. Electron Spectrosc. Relat. Phenom. 124 25
[16] Bundaleski N, Belhaj M, Gineste T and Teodoro O M N D 2015 Vacuum 13th European Vacuum Conf. Joint Meeting with 7th European Topical Conf. on Hard Coatings and 9th Iberian Vacuum Meeting 122 255
[17] Dunaevsky A, Raitises Y and Fisch N J 2003 Phys. Plasmas 10 2574
[18] Lin Y and Joy D C 2005 Surf. Interface Anal. 37 895
[19] Ooka K, Dunn B and Mackenzie J D 1973 J. Non-Cryst. Solids 12 1
[20] Israelachvili J 2011 Intermolecular and Surface Forces 3rd edn (Boston: Academic)
[21] Götzinger M and Peukert W 2004 Langmuir 20 5298
[22] LaMarche C Q, Leadley S, Liu P, Kellogg K M and Hrenya C M 2017 Chem. Eng. Sci. 158 140
[23] Schwan J, Wang X, Hsu H-W, Grün E and Horányi M 2017 Geophys. Res. Lett. 44 3059
[24] Heijmans L C J 2017 Quantifying plasma particle lofting PhD Thesis Eindhoven University of Technology, Eindhoven