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Dust mitigation technology for lunar exploration utilizing an electron beam

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ABSTRACT

Dust mobilized on the lunar surface due to natural processes and/or human activities can readily stick to spacesuits, optical devices, and mechanical components, for example. This may lead to dust hazards that have been considered as one of the technical challenges for future lunar exploration. Several dust mitigation technologies have been investigated over the past years. Here we present a new method utilizing an electron beam to shed dust off of surfaces. Recent studies on electrostatic dust lofting have shown that the emission and absorption of secondary electrons or photoelectrons inside microcavities forming between dust particles can cause the buildup of substantial negative charges on the surrounding particles. The subsequent repulsive forces between these particles can cause their release from the surface. Fine-sized lunar simulant particles (JSC-1A, <25 μm in diameter) are used in our experiments. The cleaning performance is tested against the electron beam energy and current density, the surface material, as well as thickness of the initial dust layer. It is shown that the overall cleanliness can reach 75–85% on the timescale of ~100 s with the optimized electron beam parameters (~230 eV and minimum current density between 1.5 and 3 μA/cm^2), depending on the thickness of the initial dust layer. The maximum cleanliness is found to be similar between a spacesuit sample and a glass surface. Future work will be focused on removal of the last layer of dust particles and an alternative method using ultraviolet (UV) light.

1. Introduction

The lunar surface is covered by a layer of dust particles, called regolith. These dust particles can be stirred up due to robotic and/or human exploration activities, or can be released by natural processes such as meteoroid impacts and electrostatic lofting. As reported from the Apollo missions, these dust particles can readily stick to surfaces, such as spacesuits, optical lenses and thermal blankets, causing a series of problems. Spacesuits were found damaged by abrasive lunar dust [1]. Laser retroflectors on the lunar surface have been reported to show reduced light reflectance over time, likely due to dust accumulation on their surfaces [2,3]. Radiators and thermal control surfaces (TCSs) covered by dust showed degradation in their performance [4,5]. Dust interfered with the lunar Extravehicular Activity (EVA) systems [6]. Solar panels covered by dust yield a lower power output [7]. Dust can clog mechanical joints and seals, causing failures of these parts. In addition to mechanical concerns, dust brought back to living quarters could lead to serious health risks when inhaled by astronauts [8,9]. As said above, lunar dust hazards can be problematic and have been recognized as one of the major technical challenges for future human and robotic exploration on the lunar surface.

Over the past decades, several dust mitigation technologies have been studied and developed [10]. These technologies can be divided into four categories: fluidal methods, mechanical methods, electrodynamic methods and passive methods. Fluidal methods include using liquid jets, foams and compressed gases to remove dust from the surfaces [11–13]. Mechanical methods apply brushes (e.g., nylon bristles) or vibrating mechanisms to clean dust. The brushing technique has been used in the Apollo missions. Gaier et al. [4,5] performed a series of experiments on the effectiveness of various brushes for TCSs. Electrodynamics Dust Shield (EDS) has been extensively studied [e.g., [14–19]. The basic idea is to apply oscillating high-voltages on electrodes embedded beneath the surface of an equipment to shed dust. This technique is expected to be more efficient in the lunar environment because lunar dust is charged by solar wind plasma, solar radiation and/or triboelectric effects. In passive methods, surfaces are modified (e.g., through ion implantation) to reduce the dust-surface adhesive force [5,20–22]. Recently, dust shedding with plasma discharging was studied. It was demonstrated that dust

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was removed from a glass sphere exposed to a plasma with an electron beam [23,24]. Shooting a plasma jet (1–2 kV) to dust-covered surfaces can effectively remove the dust [25]. This plasma jet technique was originally developed for dust mitigation for exploration on the Martian surface which has a 4 Torr atmosphere that can be discharged to create a high-density plasma.

Each of the aforementioned technologies has its advantages and disadvantages, which have been well summarized by Afshar-Mohajer et al. [10]. Selection of the most appropriate methods depends on the characteristics of the dust, surface properties, and application scenarios. Hybrid use of these technologies is highly recommended to achieve the best cleaning results. Here we present a new method utilizing an electron beam to charge dust particles to cause them to jump off of surfaces as a result of electrostatic forces. This method aims to clean fine-sized dust particles (<25 μm in diameter) that have been recognized as a challenge in dust mitigation technology development for several applications.

2. Dust shedding mechanism utilizing an electron beam

Dust charging and lofting on surfaces in various plasma environments has attracted much attention over the past years. Its studies have broad applications to semiconductor manufacturing [26], fusion plasmas [27], as well as dust transport and levitation on airless planetary bodies [28]. It has been shown that introducing an electron beam to a dusty surface can release dust particles from surfaces [23,24,29]. Several theories have been developed to understand possible dust release mechanisms [24,30,31]. However, none of them could fully explain the laboratory results. Recently, a series of new laboratory experiments [32–36] and a simulation work [37] have advanced our understanding of the fundamental mechanisms and characteristics of such electrostatic processes. It has been shown that dust particles can gain enough charge to be released from surfaces not only by being exposed to an electron beam but also by being exposed to ultraviolet (UV) light. Based on these new experimental discoveries, a new "patched charge model" has been developed [32]. It is briefly described as follows.

Dusty surfaces have a unique feature of microcavities forming between dust particles. As illustrated in Fig. 1a, when electrons or photons enter through a small gap and hit the blue surface patch of a dust particle below the top layer surface, secondary electrons or photoelectrons are emitted. A fraction of these emitted electrons is absorbed inside the microcavity and deposits negative charges on the surrounding dust particles (red patches). An enormously large electric field is formed across the cavity because of its small size (on the order of microns), resulting a buildup of substantial negative charges on the surrounding particles. The resulting repulsive force between these negatively charged particles is large enough to overcome the particle-particle cohesive or particle-surface adhesive force and the gravitational force, causing release of these dust particles.

It has been shown that single-sized dust particles up to 60 μm in diameter or aggregates as large as 140 μm in diameter can be released from surfaces under exposure to a 120 eV electron beam [32]. In this experiment, we performed a series of tests to find the optimized electron beam parameters to effectively shed dust off of surfaces.

3. Experimental setup and surface cleanliness analysis method

The experiment was carried out in a 50 cm diameter and 28 cm tall vacuum chamber (Fig. 1b). JSC-1A lunar simulant particles ($\rho \sim 2.9 \times 10^3$ kg/m^3, <25 μm in diameter) were deposited on a test sample (2.5 cm × 5 cm) attached to a substrate. The deposition procedure is described later in this section. The substrate was attached to a shaft rotated to have the substrate surface at 45° relative to the horizontal line. The entire sample surface was approximately uniformly exposed to an electron beam emitted from a negatively biased hot filament mounted on the top of the chamber about 20 cm above the sample surface. In

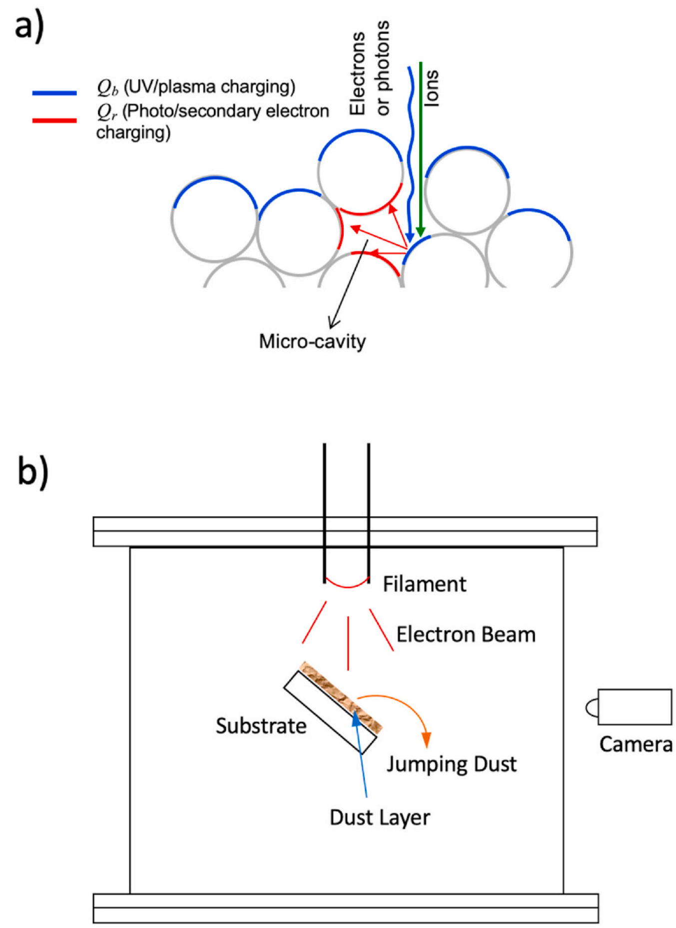

Fig. 1. A) Patched charge model for a dusty surface [32]. Inside a microcavity between dust particles, the blue surface patch exposed to electron beam or UV emits secondary electrons or photoelectrons, which then deposit on the red surface patches of the surrounding particles; b) Schematic of the experimental setup. An electron beam is generated using a negatively biased hot filament. A substrate covered with lunar simulant dust (JSC-1A, < 25 μm in diameter) is set at 45° relative to the horizontal line and exposed to the beam. Dust jumping off the surface is recorded by a high-speed video camera at 2000 fps. The changes in the surface cleanliness over time are recorded by a regular-speed video camera. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the vacuum condition, the emitted electrons create space charge effects which limit the beam current emitted from the filament. To reach higher beam currents, a low-density plasma was created by feeding in a low-pressure (~0.2 mTorr) argon gas that was ionized by the electron beam. For lunar applications this space-charge-limit effect may be minimized by attaching a small gas container to an electron source to slowly leak gas out of the source or having the source closer to the target surface. The beam current density at the sample surface was measured by a disc Langmuir probe [34,38]. Dust released from the surface was recorded by a high-speed video camera at 2000 fps to demonstrate the shedding process. Fig. 2 (left) shows that a large flux of dust particles jumps off of a glass surface as a result of exposure to the electron beam (230 eV, 1.5 μA/cm^2).

A regular-speed video camera was used to record the initial surface cleanliness and its changes during the dust shedding process. The camera's gamma correction was found to be 1 by calibrating it with the brightness derived from the images. Fig. 2 (right) shows the images of the glass surface before and after the shedding process. The surface cleanliness defines the dust coverage of the test sample surface (the lower cleanliness the higher dust coverage). In our experiments, the

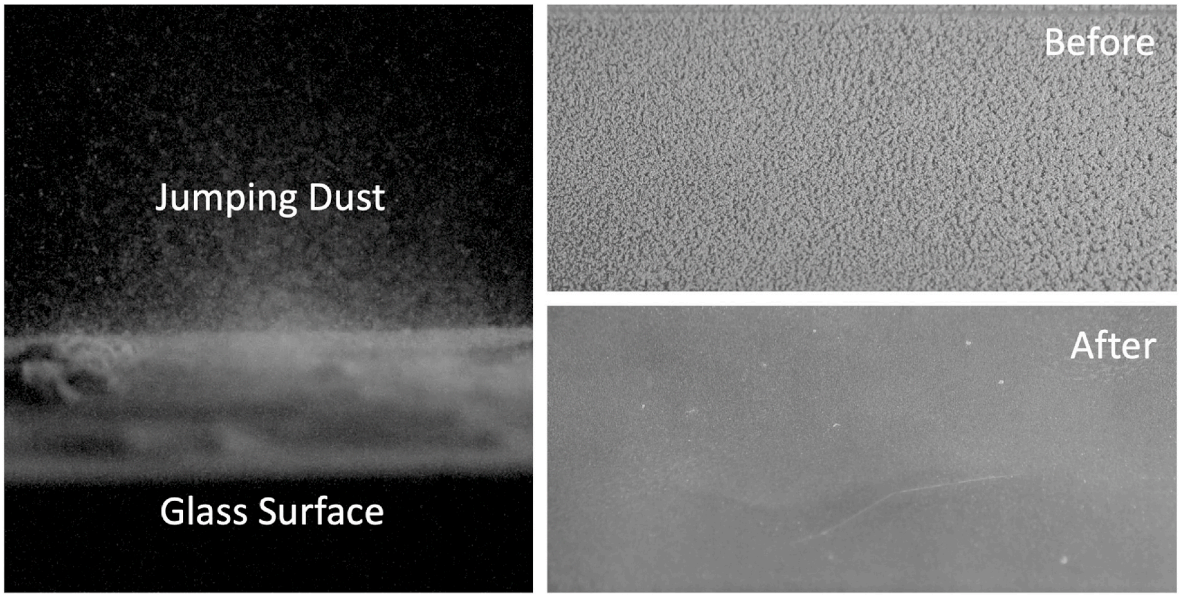

Fig. 2. Left: Dust jumping off a glass surface due to exposure to an electron beam (230 eV, 1.5 μA/cm^2); Right: Images of the glass surface before and after the beam exposure.

surface cleanliness C is conveniently defined as

$$C = (L_s - L_d) / (L_c - L_d) \tag{1}$$

where L_s is the average pixel brightness of the entire sample surface, L_c is the average pixel brightness of the clean surface (no dust) and L_d is the average pixel brightness of the surface fully covered by dust.

In order to create a controlled and consistent dust deposition on the test sample, we followed the following procedure: 1) Load the lunar simulant on a sieve (mesh opening: 25 μm); 2) Tap the sieve to let the simulant fall on the sample surface to create an approximately uniform deposition; and 3) Record an image and analyze the sample surface brightness to define the initial surface cleanliness using Eq. (1). In our experiments, we focused on cleaning the sample surface that is not fully covered by dust (i.e., $C > 0$). However, we noticed that the deposition does not create a perfect mono-layer of dust on the sample surface. Instead, dust particles can accumulate on top of each other due to inter-particle cohesion, forming a multi-layer deposition. The surface cleanliness is therefore correlated with the thickness of the dust layer as well. The lower cleanliness gives both the higher dust coverage and the thicker dust layer. As shown in Section 4, the cleaning efficiency is affected by the thickness.

We performed a series of tests to find the optimized electron beam current density and energy. The cleaning effectiveness was tested with different surface materials and thicknesses of the initial dust layer. Each of the tests included 2–4 trials. Their averaged results are shown in Figs. 3–6 with the standard deviations as error bars.

4. Results and discussion

1) Electron beam current density and energy

The optimized beam current density and energy were tested with a spacesuit sample covered by JSC-1A dust with a medium thick layer (C = 37.5%). The beam current density was varied between 0.3 and 6.1 μA/cm^2. The beam energy was set at ~230 eV which is known to yield a relatively high secondary electron emission for most materials [39]. Fig. 3a shows the cleaning process as a function of time. The maximum cleanliness reached ~75% for all the beam current densities. The time

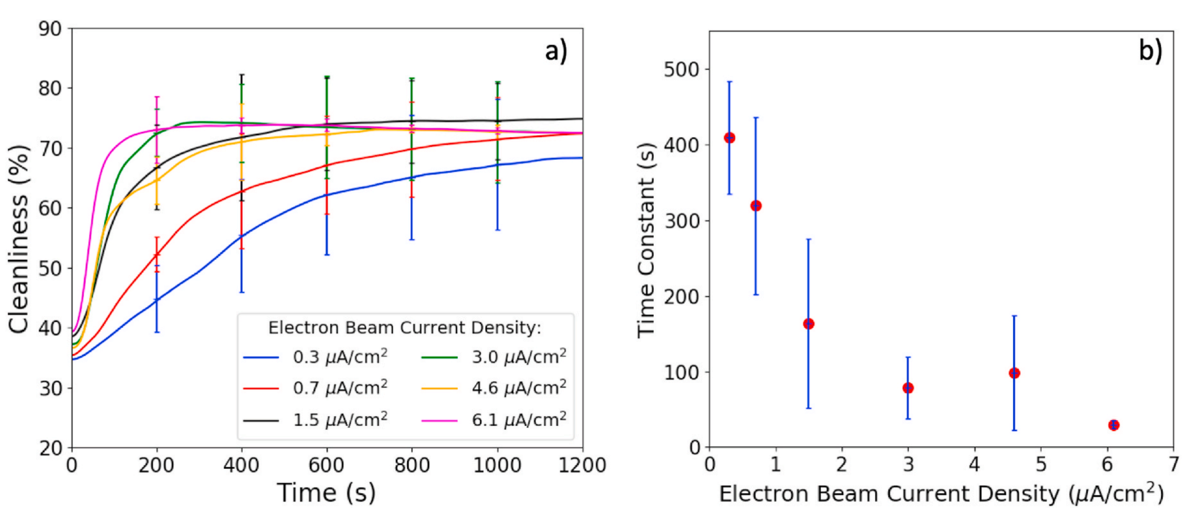

Fig. 3. a) Temporal cleaning process profiles with different electron beam current densities. The beam energy is 230 V. The process begins with a medium thick dust layer on a spacesuit sample surface; b) Time constant of the cleaning process to reach the maximum cleanliness.

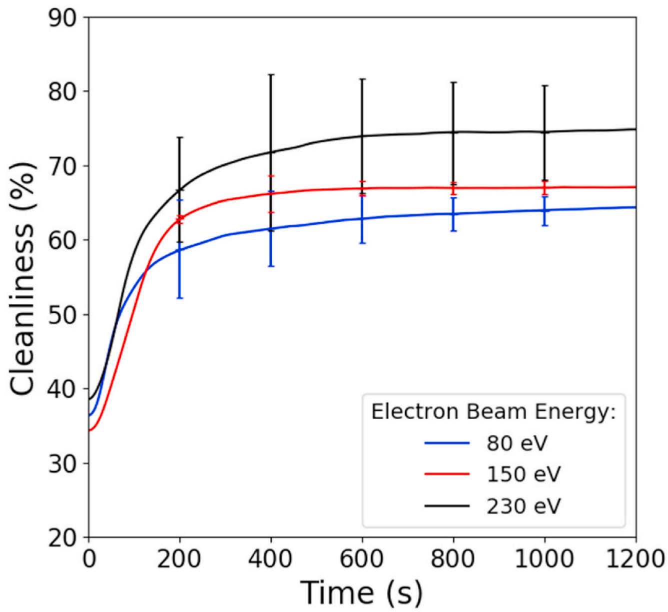

Fig. 4. Temporal cleaning process profiles with different electron beam energies. The beam current density is 1.5 μA/cm^2. The process begins with a medium thick dust layer on a spacesuit sample surface.

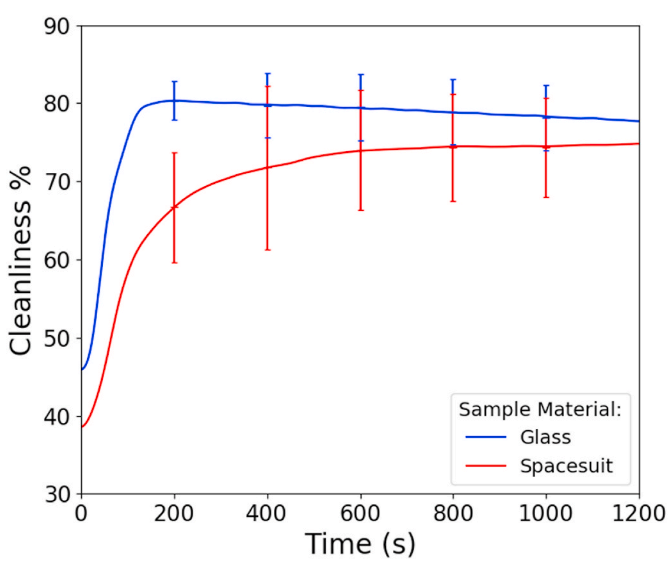

Fig. 5. Temporal cleaning process profiles with different surface materials covered by a medium thick layer of dust. The electron beam energy and current density are 230 eV and 1.5 μA/cm^2, respectively.

constant (defined as the time for the cleanliness increase to reach 1-1/*e* ≈ 63.2% between the initial and final values) of the cleaning process decreases as the current density increases, as shown in Fig. 3b. The time constant tends to reach the plateau ~100 s at the current density between 1.5 and 3 μA/cm^2. The results shown in Fig. 3b can be explained as follows. The decrease rate of the time constant for dust cleaning approximately agrees with the increase rate of the electron beam current density because the charging time of dust particles is inversely proportional to the current density. Higher current density results in shorter charging time and thus faster dust release. When the charging process is faster than dust motion, the release rate is limited by dust motion and reaches the plateau.

The beam energy dependence was tested between 60 and 400 eV. It was found that the threshold energy to turn on the cleaning process was

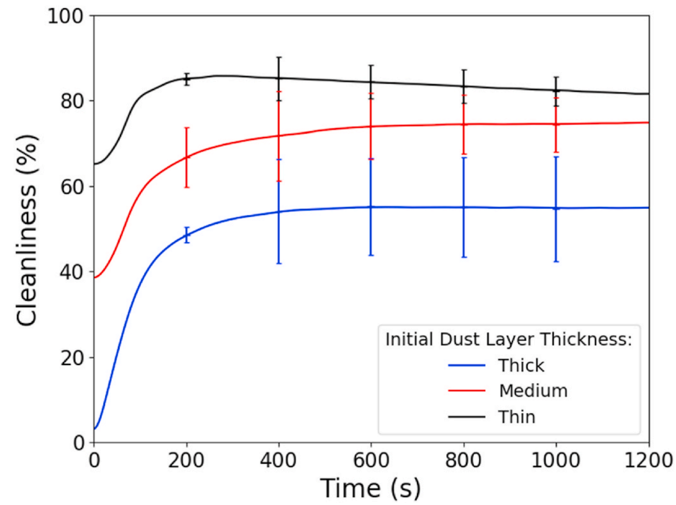

Fig. 6. Temporal cleaning process profiles with different initial thicknesses of the dust layer on the spacesuit sample surface. The electron beam energy and current density are 230 eV and 1.5 μA/cm^2, respectively.

~80 eV, which is the minimum energy of incident electrons to generate enough secondary electrons to create a significant microcavity charging effect, as described in section 2. Fig. 4 shows the cleaning processes with the beam energy at 80 eV, 150 eV and 230 eV. It is shown that the cleanliness increases as the beam energy increases. It was found that dust was hardly removed when the beam energy was 400 eV (not shown). It is known that the secondary electron yield rises to a peak value and then falls as the primary electron energy increases [39]. These results may indicate that the secondary electron yield from lunar simulant peaks at the primary electron energy around 230 eV. An electron beam with energy ~230 eV and minimum current density between 1.5 and 3 μA/cm^2 is shown to be most effective to shed dust off surfaces.

2) Surface material

Both an Apollo spacesuit sample and a glass plate were tested with the optimized beam energy and current density (230 eV and 1.5 μA/cm^2). Fig. 5 shows that the cleanliness for both materials follows a similar trend.

3) Dust layer thickness

In this test, the spacesuit sample was covered by a dust layer of three different thicknesses in terms of a cleanliness level: 5%, 40% and 65%. Fig. 6 shows that the cleanliness varies with the initial dust layer thickness. The thinner dust layer ends up with a higher cleanliness (as high as ~85%). A possible explanation is that in a thicker layer, dust particles below the very top layer are more compact due to gravity, resulting in larger inter-particle cohesive forces to be overcome. Such compaction effect on dust release has been shown in previous experiments [34,36]. On the lunar surface, this effect is expected to be reduced due to its lower gravity. As also suggested above, a hybrid mitigation strategy can be used. For example, an initially thick dust layer can be removed by other methods such as brushing or vibrating followed by the electron beam method to clean the rest of the layer that is relatively thin.

Overall, our measurements show that surfaces covered by a medium to thin layer of fine-sized dust can be cleaned utilizing an electron beam to reach a cleanliness level as high as 75–85% within a relatively short period of time (<1 min). Additionally, charge buildup on surfaces exposed to the electron beam was not observed to lead to any electrostatic discharge in any of our tests.

5. Conclusion and future work

We have demonstrated a new method utilizing an electron beam to charge fine-sized dust particles and shed them off of various surfaces as a result of electrostatic forces. This method was based on recent discoveries in electrostatic dust lofting studies. Secondary electrons created on a dusty surface due to exposure to an electron beam can be absorbed inside microcavities between dust particles, causing a buildup of substantial negative charges on the surrounding particles. The repulsive forces between these largely negatively charged particles cause their release from the surface. Surfaces covered by JSC-1A lunar simulant particles (<25 μm in diameter) were tested using an electron beam with different surface materials and thicknesses of the initial dust layer. It was found that the overall cleanliness for a medium to thin dust layer (40–65% initial) can reach 75–85% on a timescale of ~100 s with the optimized electron beam energy ~230 eV and minimum current density between 1.5 and 3 $\mu A/cm^2$. The cleanliness was found to be similar between a spacesuit sample and a glass plate.

The remaining 15–25% dust coverage was mainly a monolayer of dust particles as shown in Fig. 2 (right). Removal of these particles will be studied in future work. Based on the patched charge model [32], the emission and absorption of photoelectrons inside microcavities between dust particles can also create large negative charges on them, causing their release as a result of large inter-particle repulsive forces. An alternative dust removal method using a short wavelength UV light will be also tested in future work.

Interest declaration

The results presented in this paper are interesting to the lunar exploration, dust mitigation and electric charging communities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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