Removal of floating dust in glow discharge using plasma jet

C. M. Ticoş,[a)] I. Jepu, C. P. Lungu, P. Chiru, V. Zaroschi, and A. M. Lungu
National Institute for Lasers, Plasma and Radiation Physics, 077125 Bucharest, Romania

(Received 30 April 2010; accepted 15 June 2010; published online 6 July 2010)

Dust can be an inconvenient source of impurities in plasma processing reactors and in many cases it can cause damage to the plasma-treated surfaces. A technique for dust expulsion out of the trapping region in plasma is presented here, based on the wind force exerted on dust particles by a pulsed plasma jet. Its applicability is demonstrated by removing floating dust in the sheath of parallel-plate capacitive radio-frequency plasma. © *2010 American Institute of Physics*.
[doi:10.1063/1.3460293]

Dust in plasma is a two-facet problem which can be approached depending on purpose and utility. On one side there is wide interest for basic science focused on aspects of dust-plasma interactions.[1] For this purpose dust is deliberately supplied to the plasma. On the other side, in many plasma applications dust is an unwanted element and attention is drawn to find techniques for removing it.[2] Examples are in industrial plasma processing where dust is a byproduct of the chemical reactions between the gases and the wafer or in magnetically confined fusion plasmas where dust is stripped away from the surfaces exposed to plasma particles fluxes.[3,4] In plasma reactors used for etching or polymerization, the use of SiH_4 leads to coagulation of nanoparticles and eventually microparticles. The accumulation of mass is accompanied by collection of electrical charges and the particles eventually get trapped by the electric force in the sheath near the bottom electrode. When their mass reaches a critical value, they become too heavy and free fall to the surface.

In this paper we present a technique for expulsion of dust particles trapped within the sheath of radio-frequency (rf) plasma produced between two-parallel plate electrodes. The technique is based on the action of plasma drag force on the dust particles.[5,6] Microspheres made of melamine formaldehyde are released into the rf plasma and are levitated by the electric force. A pulsed discharge created in the vicinity of the dust cloud launches a plasma jet at speeds of a few kilometers per second with a directed motion toward the dust particles. Momentum transfer from flowing ions to the dust particles results in dust displacement at speeds of a few meter per second. The dust particles are transported by the jet outside the trapping region where they free fall. Electrons from the plasma jet impacting with the dust grains can have mostly an influence on the charge accumulated on the dust particles.

Several methods have been proposed for dust removal in plasma reactors which are based on radiation pressure from high power laser beam,[7] electrical potential wells created by synchronized biased strips placed below the rf electrodes,[8] gravitational traps,[9,10] combination of electrostatic trap and gas injection[2] or thermophoretic force.[11] Each of these methods has its own advantages and limitations. For example, a high power laser beam does not interfere with the plasma but it is effective in a very localized region spanned by the beam, whether it is a thin plane or a cylindrical section, and it requires several scans in order to cover a wider volume. Dust removal by neutral gas-drag requires puffing of gas at higher pressure in the reactor chamber which in principle can affect the plasma-surface process, while creation of electrical potential wells relies heavily on the charge of the dust particles.

The present technique has several key advantages. The generated fast ion flow is effective on large (a few microns) as well as small (tens of nanometers) dust particles with any shapes and in principle made of any type of material. The smaller the particles, the greater is the efficiency of the method, as it is well known that submicron particles can be easily manipulated by the ion drag force. In terms of momentum transfer to the dust particles through collisions, accelerated ions can be more effective than neutral atoms. In plasma jets, ions can flow with speed up to 60 km/s, which is at least an order of magnitude higher than the sound speed of puffed neutral atoms.[12] Moreover, the charge on the dust particles is not a limiting factor but rather can have an enhancing effect on ion collection.

The trapped dust particles can be plasma-dragged over distances of several centimeters allowing our technique applicability to instances where the particles hover over larger surfaces. The discharge used to produce the plasma jet can be initiated in the working gas of the undergoing plasma-surface process and at the same pressure without additional gas injection. Concerning the parameters of the plasma where dust is resident, the proposed ion drag technique is optimal in tenuous low ionized gases, similar to those produced in processing reactors ($n_e \approx 10^{14}-10^{15}$ m^{-3}). As an example, we apply our method to a capacitive rf plasma with parallel electrodes, a type of configuration widely used in plasma processing.

The rf plasma is produced in argon at pressures between 155 and 265 mtorr. The bottom electrode is driven by an rf voltage at 13.56 MHz and coupled to the power source through a matching network, as shown in Fig. 1. About 6–8 W are supplied into the plasma with less than 10% reflected power when the network is tuned. The top electrode is grounded. Monodispersive particles with a diameter $2r_d = 6.07$ μm are introduced by shaking a cup inside the plasma. The dust settle in the sheath above the rf electrode and are confined inside a circular region cut in the electrode with 3 cm in diameter and 1.5 mm depth. Typical electron density and temperature for this setup are $1-3\times 10^{15}$ m^{-3} and 2–3.4 eV, respectively.[13]

[a)]Electronic mail: catalin.ticos@inflpr.ro.

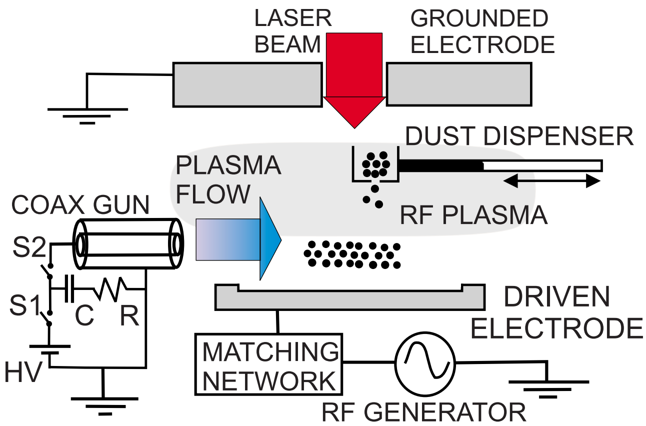

FIG. 1. (Color online) Setup with coaxial gun and rf plasma.

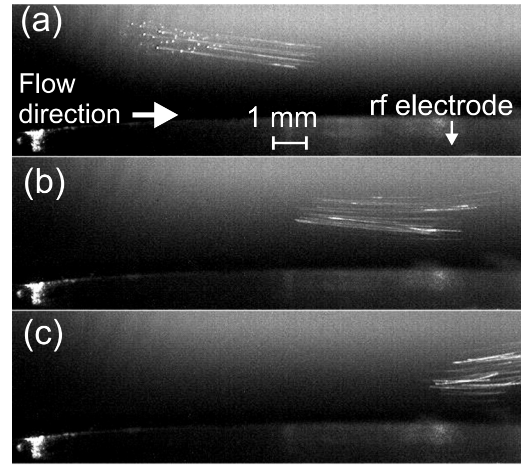

FIG. 2. Dust expulsion for a 1 kV coaxial gun shot. Static dust particles shown in (a) are put in motion by the plasma jet. The edge of the trapping region is seen in the background.

The plasma jet is created inside a miniature plasma gun with two coaxial electrodes, a center rod, and a cylindrical tube.[14] The gun electrodes are powered from a capacitor with $C=12\ \mu F$ in series with a resistor $R=90\ \Omega$. The capacitor is charged up to 2 kV from a high-voltage dc power supply at constant current of 2 mA. The charging/firing state of the capacitor is controlled by two high-voltage switches, S1 and S2, respectively. The gun operates in a single-pulse regime, with a few minutes between consecutive shots. The plasma jet is expelled by the $J\times B$ force where J is the current density between the gun electrodes and B is the inner self-created magnetic field.[12] Peak currents of 5–23 A have been measured with a Rogowski coil (Pearson current probe), for voltages between 0.5 kV and 2 kV, respectively. The current pulse is overdamped and drops to ≈ 1 A after 1.5 to 2.6 ms, for the range above. The plasma jet is self-collimated over a distance of 30 cm. Its diameter of ≈ 3 cm is about the same as the gun inner diameter. The plasma flow speed is between 3.1 and 3.9 km/s. It has been measured by high-speed imaging of the jet column for an exposure of 13.7 μs. The flow speed increases slightly with the applied voltage, at constant pressure. The edge of the gun is placed at 23 mm from the dust confining region.

The dust particles are illuminated with a vertical sheath of light by passing the beam emitted from a laser diode (25 mW at 680 nm) through a cylindrical lens. The particles are imaged from a side window of the vacuum chamber using a Micro-Nikkor 60 mm f/2.8D lens, a teleconverter (2×) and a set of three spacers with total length of 68 mm mounted on a FastCam PCI 1024. A red filter with a passing threshold at 650 nm is put in front of the camera lens in order to cut out the plasma radiation. The view of the camera is perpendicular on the direction of jet propagation.

A dust cloud levitated about 5 mm above the driven electrode is initially at rest at the extremity of the confining region, in Fig. 2(a). A small electrode inclination of about 3° allows the particles to slide and reach for the lowest gravitational energy within the sheath which is slightly deformed due to a cut in the electrode. Viewed from the side, the plasma sheath resembles a wide inverted bell curve. When the coaxial gun is fired the particles are dragged in the jet direction as shown in Figs. 2(a)–2(c). The exposure of the camera is set in Fig. 2(a) such that it is able to capture the equilibrium position of the particles as well as their trajectories when they are dragged by the plasma jet. The dust speed can be deduced by measuring the trace of each particle $v_d=L_{tr}/T_{exp}$, where L_{tr} is the trace length and T_{exp} is the exposure time: $v_d=12.1-14$ m/s in Fig. 2(b). In all images presenting dust $T_{exp}=0.33$ ms while the frame rate is 3000 fps. The obtained dust speed is useful for calculating the length of the dust trajectories and estimating their falling distance. The particles move slower for lower plasma ejection speed and eventually come to a stop due to friction with the neutral gas as shown in Fig. 3. For a 0.5 kV gun shot, the dust cloud shown in Fig. 3(a) is displaced to a new position at 3.9 mm as shown in Fig. 3(b), while for a 0.8 kV shot, the displacement increases to 12.5 mm, as can be seen in Fig. 3(d). A useful feature for our technique which can be easily observed in Figs. 2(a)–2(c) is that the dust particles do not repel each other as they stream out of the confining region, in spite of their negative charge. This situation is similar to that of dust particles forming a crystal in the rf sheath: ions flowing through the crystal have a screening effect and can keep the particles bound together. When the particles lose much of their kinetic energy, at the end of their straight trajectory, they tend to have a random motion, with a few vertical oscillations, due probably to reciprocal repulsion forces, as it can be seen in Figs. 3(b) and 3(d). Then the particles move

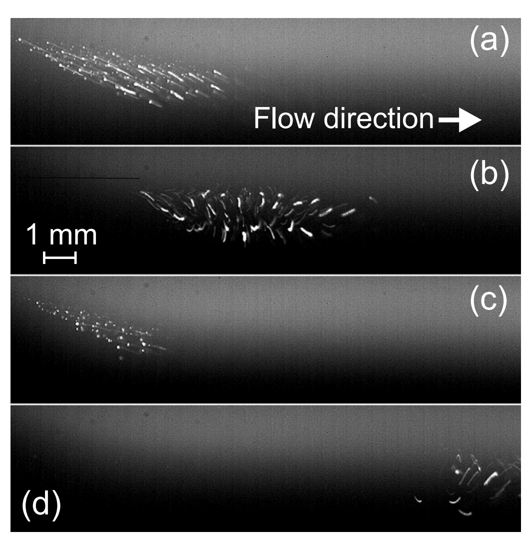

FIG. 3. Dust displacement by a coaxial gun shot fired at 0.5 kV for (a) and (b), and 0.8 kV for (c) and (d).

back slowly toward their initial equilibrium position, to the bottom of the confining potential well.

All dust particles imaged in the vertical plane of the dust cloud are being transported by the plasma jet, thus making our technique fairly efficient. Good removal of dust is in principle dependent on the geometry of the setup. From our experience, we observed that placing the gun too close (a few millimeter) or too far (>35 mm) from the dust cloud has an opposite effect. In the first case the jet can perturb the sheath strongly and shakes the particles vertically which such large amplitude that they will fall to the electrode. In the second case, the jet eventually gets deflected at the rf sheath boundary, and the dust particles are barely displaced. It seems that dust removal is optimal at about 1 kV, in our setup. More powerful jets created by higher discharge voltages can produce turbulence at the interface with the rf plasma and drag the dust particles in all directions, including toward the electrode. One observation is that the expelled particles follow a curved trajectory, near the sheath boundary as shown in Figs. 2(b) and 2(c). The particles are at all times levitated by the electrical force given by the sheath electric field, which equilibrates the force of gravity.

The charge Q_d accumulated on a dust particle is established by the net ion and electron currents to the particle's surface. The trajectories of ions colliding with the dust particle are considered in the orbital motion limited formalism.[15] The spherical dust particle is much smaller than the plasma screening length and its potential is $V_d=Q_d/4\pi\varepsilon_0 r_d$. Electrons follow a Boltzmann distribution with density $\propto\exp(eV_d/k_BT_e)$. The ion drag force exerted on a dust particle has two components: the collisional direct impact force which is dominant in our case, and the long-range Coulombic force which we neglect. For ions obeying a Maxwellian distribution shifted by the flow velocity v_f,[16] $F_{coll}=n_i r_d^2 m_i v_{ti} G(s)\sqrt{\pi}/2$, where $G(s)=\sqrt{\pi}/2[4s^2+4-1/s^2-2(1/s^2-2)\chi]\mathrm{erf}(s)+(2s+1/s+2\chi/s)\exp(-s^2)$, $v_{ti}=\sqrt{2k_BT_i/m_i}$ is the ion thermal speed, $s=v_f/v_{ti}$, and $\chi=-eV_d/k_BT_i$. Here $T_i=0.025$ eV, $T_e=3$ eV, $v_f=3.5$ km/s, and the jet duration is 175 ms. In the rf plasma $V_d\approx-2.5k_BT_e(=-7.5\text{ V})$ and $Q_d\approx 15.7\times10^3$ e, where $e=-1.6\times10^{-19}$ C. Considering that dust acceleration is determined by the ion drag force, we can match the terminal dust speed with the experiment for jet densities $n_i=1-3\times10^{17}\text{ m}^{-3}$.

Displacement of dust particles on distances of the order of tens of centimeters is achievable by ion flows fired from a low-energy coaxial gun. The effectiveness of our proposed method is demonstrated in argon gas but it is applicable also for lighter gases. Dust acceleration by plasma jets has been demonstrated in hydrogen, deuterium, and helium.[12] Also, the fact the dust particles are strongly coupled electrostatically does not constitute an impediment for our dust removal technique.

This work was supported by UEFISCSU under Contract No. RP-10 within PNCDI2, and by ANCS under contract Nucleu-LAPLAS 2010.

[1]P. K. Shukla and B. Eliasson, Rev. Mod. Phys. **81**, 25 (2009).
[2]G. S. Selwyn, U.S. Patent No. 5,849,135 (15 December 1998).
[3]L. Boufendi and A. Bouchoule, Plasma Sources Sci. Technol. **11**, A211 (2002).
[4]J. Winter, V. E. Fortov, and A. P. Nefedov, J. Nucl. Mater. **290–293**, 509 (2001).
[5]M. S. Barnes, J. H. Keller, J. C. Forster, J. A. O'Neill, and D. Keith Coultas, Phys. Rev. Lett. **68**, 313 (1992).
[6]S. A. Khrapak, A. V. Ivlev, G. E. Morfill, and H. M. Thomas, Phys. Rev. E **66**, 046414 (2002).
[7]R. A. Schill, Jr., Laser Part. Beams **20**, 341 (2002).
[8]Y.-F. Li, U. Konopka, K. Jiang, T. Shimizu, H. Höfner, H. M. Thomas, and G. E. Morfill, Appl. Phys. Lett. **94**, 081502 (2009).
[9]S. Raoux, D. Cheung, M. Fodor, W. N. Taylor, and K. Fairbairn, Plasma Sources Sci. Technol. **6**, 405 (1997).
[10]Y. Kurimoto, N. Matsuda, G. Uchida, S. Iizuka, M. Suemitsu, and N. Sato, Thin Solid Films **457**, 285 (2004).
[11]S. V. Vladimirov and K. Ostrikov, Phys. Rep. **393**, 175 (2004).
[12]C. M. Ticoş, Z. Wang, G. A. Wurden, J. L. Kline, and D. S. Montgomery, Phys. Plasmas **15**, 103701 (2008).
[13]C. M. Ticoş, A. Dyson, and P. W. Smith, Plasma Sources Sci. Technol. **13**, 395 (2004).
[14]C. M. Ticoş, Z. Wang, L. A. Dorf, and G. A. Wurden, Rev. Sci. Instrum. **77**, 10E304 (2006).
[15]J. E. Allen, Phys. Scr. **45**, 497 (1992).
[16]I. H. Hutchinson, Plasma Phys. Controlled Fusion **48**, 185 (2006).