Charge neutralization of dust particles in a plasma with negative ions

Robert L. Merlino[a)] and Su-Hyun Kim
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

(Received 3 May 2006; accepted 3 July 2006; published online 28 August 2006)

Charging of dust grains in a plasma with negative ions is studied experimentally. When the relatively mobile electrons are attached to heavy negative ions, their tendency to charge the grains negatively is reduced. In a plasma in which a substantial fraction of the electrons are eliminated (positive ion/negative ion plasma), the grain charge can be reduced in magnitude nearly to zero ("decharging" or charge neutralization). If the positive ions are lighter than the negative ions, dust grains having a small net positive charge can be produced. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2338790]

Plasmas used for industrial processing often use gases that result in the formation of negative ions. For example, hydrogenated amorphous silicon semiconductors used for liquid crystal displays and photovoltaics are produced in radio frequency plasma enhanced chemical vapor deposion devices using either pure or hydrogen diluted silane (SiH_4). Silane plasmas have a high abundance of SiH_4^- ions which is considered as a major precursor for the growth of nanometer size silicon particles. As the particles grow, a significant fraction may deposit onto the films adversely affecting the performance characteristics of the integrated circuits. On the other hand, the orderly deposition of nanoparticles created in the discharge may also provide efficient technologies for the synthesis of composite materials. The plasma not only provides the genesis of the particles but also the mechanism through which they acquire an electrical charge. The charge on the dust particles is one of the crucial parameters affecting their trapping and transport. Gallagher[1] argued that for the particles to escape and deposit into the films, a large fraction must be charge neutralized, which is likely to occur when immersed in a plasma with an electron attaching gas such as silane, in which the electron density can be significantly less than the negative ion density. In electropositive plasmas, dust particles acquire a negative charge since the electron thermal velocities are much higher than the positive ion thermal velocities. When the electrons are attached to negative ions, the situation is much different since the negative ion thermal velocities are much less than those of the electrons. In fact, if a sufficient fraction of the electrons are attached to the negative ions which are heavier than the positive ions, it is possible for the dust to acquire a positive charge. Even if this extreme situation does not occur, the magnitude of the negative charge on the dust can be considerably reduced (possibly close to zero) in the presence of negative ions, rendering the dust charge neutralized. In this letter, an experiment is described in which the neutralization of dust in an electronegative plasma is observed.

The charge Q on a dust grain is related to its surface (or floating) potential V_s (relative to the plasma potential) by $Q=4\pi\varepsilon_0 a V_s$, where a is the radius of the (spherical) grain. The surface potential of a dust particle in an electronegative plasma is determined by balancing the currents due to positive ions, negative ions, and electrons.[2–4] For $V_s<0$ the condition that the total current to a grain be zero is

$$-n_e\left(\frac{kT_e}{2\pi m_e}\right)^{1/2}\exp\left(\frac{eV_s}{kT_e}\right)-n_-\left(\frac{kT_-}{2\pi m_-}\right)^{1/2}\exp\left(\frac{eV_s}{kT_-}\right)+n_+\left(\frac{kT_+}{2\pi m_+}\right)^{1/2}\left(1-\frac{eV_s}{kT_+}\right)=0, \quad (1)$$

while for $V_s>0$, the condition is

$$-n_e\left(\frac{kT_e}{2\pi m_e}\right)^{1/2}\left(1+\frac{eV_s}{kT_e}\right)-n_-\left(\frac{kT_-}{2\pi m_-}\right)^{1/2}\left(1+\frac{eV_s}{kT_-}\right)+n_+\left(\frac{kT_+}{2\pi m_+}\right)^{1/2}\exp\left(-\frac{eV_s}{kT_+}\right)=0, \quad (2)$$

where n_e, n_-, and n_+ are the electron, negative ion, and positive ion densities; m_e, m_+, and m_- are the electron, positive ion, and negative ion masses; and T_e, T_+, and T_- are the electron, positive ion, and negative ion temperatures, respectively. Figure 1 shows the solutions to Eqs. (1) and (2) for the normalized grain potential eV_s/kT_+ as a function of the relative negative ion density, n_-/n_e, for three positive ion/negative ion combinations: (a) H_2^+/SiH_3^-, (b) O_2^+/O^-, and (c) K^+/SF_6^-, and taking $T_+=T_-=T_e$. Cases (a) and (b) are chosen because they are of interest in processing plasmas while case (c) corresponds to the present experiment. Cases (a) and (b) were also chosen because they provide examples in which

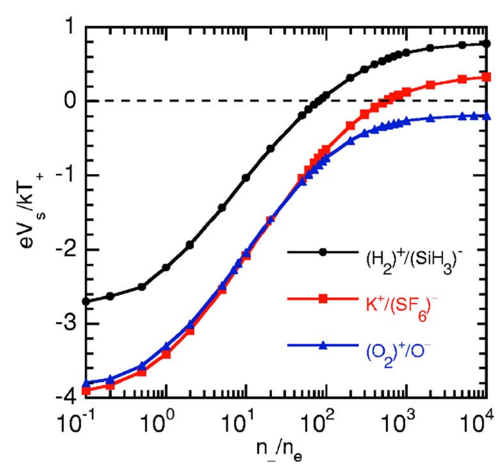

FIG. 1. (Color online) Normalized dust surface potential vs the relative negative ion density, n_-/n_e, for three positive ion/ negative ion combinations: $T_+=T_-=T_e$. The present experiment uses K^+/SF_6^-.

a)Electronic mail: robert-merlino@uiowa.edu

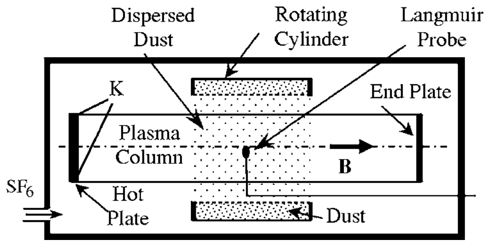

FIG. 2. Schematic of the experimental setup. The plasma source is a Q machine with K^+ positive ions. SF_6 gas can be admitted to produce a negative ion plasma. Dust can be introduced using the rotating cylinder dispenser.

$m_+/m_- < 1$ [case (a)] and $m_+/m_- > 1$ [case (b)]. For equal temperatures, and $m_+/m_- < 1$, the dust potential can be positive when the relative negative ion density is sufficiently high, since the positive ions are the more mobile species. However, when $m_+/m_- > 1$, the dust potential is reduced but does not go positive. For case (c), which corresponds to the present experiment, the dust potential decreases with increasing n_-/n_e and becomes positive for $n_-/n_e > 500$.

The experiments were carried out in a single ended Q machine[5] shown schematically in Fig. 2. The plasma is formed by surface ionization of potassium atoms on a hot (2300 K) 6 cm diameter tantalum plate which also emits thermionic electrons. The plasma is confined radially by a uniform axial magnetic field of 0.3 T, with a density of $\sim 10^{10}\ \mathrm{cm}^{-3}$ and temperatures $T_+ = T_e \approx 0.2$ eV. Negative ions are produced in the plasma by leaking in SF_6 at partial pressures up to 1 mTorr. Since the electron attachment cross section is relatively high at low electron energies, SF_6^- negative ions are readily produced in the Q machine plasma.[6] Sato[7] measured the relative electron density in a K^+ Q machine plasma under conditions that were almost identical to those used here and found that for a SF_6 partial pressure of 1 mTorr, $n_e/n_+ \sim 10^{-5}$. Under these conditions, we have essentially a positive ion/negative ion plasma. Dust can be dispersed into the plasma over the middle third of its 1 m length, using the rotating cylinder dispenser described in detail elsewhere.[8] The inner wall of the cylinder is lined with aluminum wool embedded with hollow glass microspheres (polydisperse with the majority of microspheres $\sim 35\ \mu$m diameter). When the cylinder is rotated, the glass microspheres fall through the plasma to the bottom of the cylinder where they are recycled.

The main diagnostic was a planar disk (diameter of 3 mm) Langmuir probe with its surface oriented perpendicular to the magnetic field. Analysis of the I-V characteristics of the Langmuir probe is used to provide measurements of the probe floating potential V_f and the plasma space potential V_p (from the location of the maximum in the first derivative of the probe current). A measurement of the positive and negative probe saturation currents before and after the dust is introduced can be used to determine the magnitude and sign of the charge on the dust.[9] In a plasma with no negative ions, but with dust of charge Q and density n_d, the charge neutrality condition is $en_+ + Qn_d = en_e$. This can be written as $Qn_d/en_+ = \eta - 1$, where $\eta = n_e/n_+$. The quantity η can be determined by measurements of the ratios of the electron and ion saturation currents with and without dust, $\eta = (I_e/I_{e0})/(I_+/I_{+0})$, where I_{e0} and I_{+0} are the electron and ion saturation currents with no dust present and I_e and I_+ are the electron and ion saturation currents with dust present.[9] In terms of the saturation current ratios then $Qn_d/en_{+0} = I_e/I_{e0} - I_+/I_{+0}$. Now in the negative ion plasma when a sufficient fraction of the electrons are attached to the negative ions so that their effect on dust charging is negligible, the charge neutrality condition is $en_+ + Qn_d = en_-$. In this case $Qn_d/en_{+0} = I_-/I_{-0} - I_+/I_{+0}$, where I_- and I_{-0} are the negative ion saturation currents with and without dust. Both the magnitude and sign of Q can be inferred by observing the changes in the saturation currents. Figure 3(a) shows the probe I-V curves with dust on and on in a plasma with no negative ions, $P(SF_6) = 0$. In the I-V curves, positive currents correspond to the collection of the negative particles—electrons or negative ions. When the dust is present the electron current is reduced by some 10%–15% since some of the electrons now reside on the heavy dust particles. On the other hand, the ion current is barely affected by the dust, as observed in earlier dusty plasma experiments,[9] since most of the charge in this case is provided by the electrons. From the reduction in the electron current we find that $Qn_d/en_{+0} \approx -0.10 \pm 0.05$, so that $Q < 0$. Figure 3(b) shows the corresponding curves with $P(SF_6) = 1$ mTorr. In this case, the reductions in the negative ion and positive ion saturation currents are comparable, and we find that $Qn_d/en_{+0} \approx -0.03 \pm 0.05$, or that $Q \lesssim 0$, the dust charge has been largely neutralized, in qualitative agreement with the theoretical result in Fig. 1. Only relatively moderate amounts of SF_6 are required to significantly reduce the negative charge on the dust. For example, with $P(SF_6) \sim 0.1$ mTorr, the negative charge is reduced by about a factor of 10.

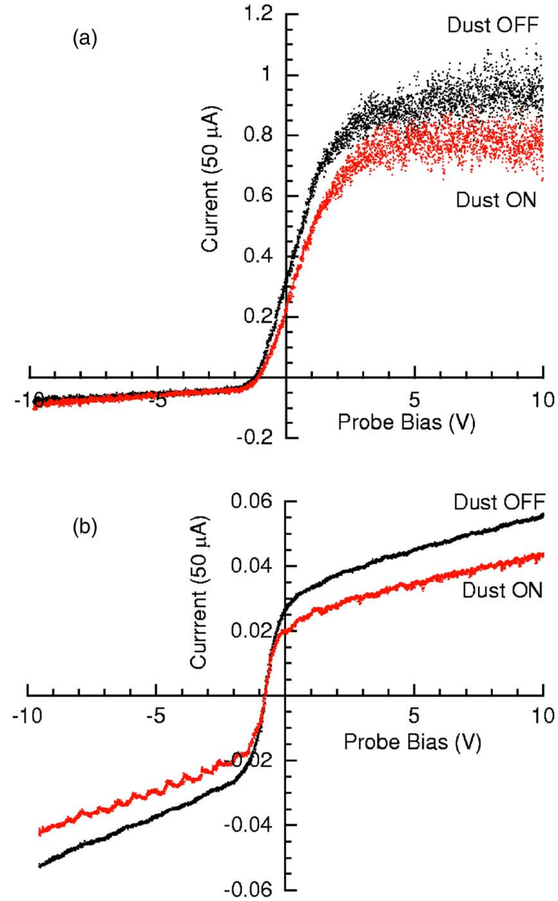

FIG. 3. (Color online) Langmuir probe I-V curves taken with dust on and dust off for (a) $P(SF_6) = 0$ mTorr and (b) $P(SF_6) = 1$ mTorr.

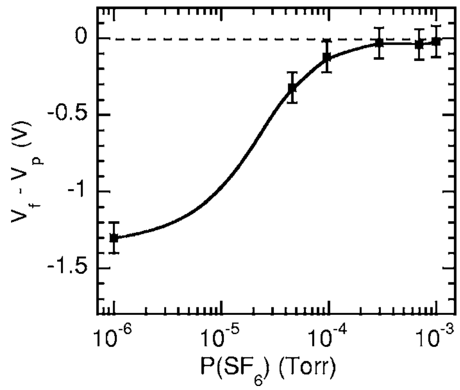

FIG. 4. Measurement of the difference between the probe floating potential V_f, and the plasma potential V_p vs $P(SF_6)$. The lowest pressure corresponds to the case in which no SF_6 was present.

To further illustrate that those conditions have been established which result in dust charge neutralization (or even positive dust) we show in Fig. 4 the measurement of the difference between the probe floating potential (V_f) and plasma potential (V_p) obtained at various values of $P(SF_6)$ up to 1 mTorr. As the SF_6 pressure is increased (increasing the concentration of negative ions relative to the electrons) the magnitude of V_f-V_p decreases and approaches 0 (or even small positive values within the error of the measurement). The dust grains also behave as tiny floating objects in the plasma so that the behavior of the probe floating potential relative to the plasma should be similar to that of the probe.

In summary, the results of an experiment investigating the charging of dust grains in a negative ion plasma have been presented. The dust charge can be controlled by varying the relative fraction of negative ions in the plasma. As the negative ion density increases, the magnitude of the dust charge is reduced and approaches zero, resulting in an effective "decharging' of the dust.

This work was supported by the U.S. Department of Energy under Grant No. DE-FG02-04ER54795.

[1]A. Gallagher, Phys. Rev. E **62**, 2690 (2000).
[2]A. A. Mamun and P. K. Shukla, Phys. Plasmas **10**, 1518 (2003).
[3]N. D'Angelo, J. Phys. D **37**, 860 (2004).
[4]B. M. Annaratone and J. E. Allen, J. Phys. D **38**, 26 (2005).
[5]R. W. Motley, *Q Machines* (Academic, San Diego, 1975), p. 2.
[6]R. K. Asundi and J. D. Craggs, Proc. Phys. Soc. London **83**, 611 (1964); A. Chutjian, Phys. Rev. Lett. **46**, 1511 (1981); A. V. Phelps and R. J. Van Brunt, J. Appl. Phys. **64**, 4269 (1988); D. P. Sheehan and N. Rynn, Rev. Sci. Instrum. **59**, 1369 (1988).
[7]N. Sato, in *Proceedings of the 1989 International Conference on Plasma Physics*, edited by A. Sen and P. K. Kaw (Indian Academy of Sciences, Bangalore, 1989), p. 79; Plasma Sources Sci. Technol. **3**, 395 (1994).
[8]W. Xu, B. Song, R. L. Merlino, and N. D'Angelo, Rev. Sci. Instrum. **63**, 5266 (1992).
[9]W. Xu, N. D'Angelo, and R. L. Merlino, J. Geophys. Res. **98**, 7843 (1993); A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Rev. Lett. **73**, 3093 (1994).