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Z. Marvi,a) T. J. M. Donders, M. Hasani, G. Klaassen, and J. Beckers

AFFILIATIONS
Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

a)Author to whom correspondence should be addressed: z.marvi@tue.nl

ABSTRACT

We experimentally demonstrate that the interaction between plasma and nanometer-sized semiconductor quantum dots (QDs) is directly connected to a change in their photoluminescence (PL) spectrum. This is done by taking in situ, high resolution, and temporally resolved spectra of the light emitted by laser-excited QDs on an electrically floating sample exposed to a low pressure argon plasma. Our results show a fast redshift of the PL emission peak indicating the quantum-confined Stark effect due to plasma-generated excess charges on the substrate and near the QD surface, while other plasma-induced (thermal and ion) effects on longer timescales could clearly be distinguished from these charging effects. The presented results and method open up pathways to direct visualization and understanding of fundamental plasma–particle interactions on nanometer length scales.

In the field of complex plasmas—i.e., ionized gases containing nanometer- to micrometer-sized particles—the charge of plasma-immersed particles is the parameter of most interest. This is because obtaining elementary knowledge regarding plasma–particle charging is the main key to understanding many fundamental processes, such as those in the planetary rings of Saturn, in strongly coupled collective particle–particle interactions, e.g., in plasma crystals in earth laboratories and in the International Space Station, and in plasma–particle interactions in the form of dust density waves (DDWs).

From an application point of view, plasma charging plays an essential role in in situ plasma-assisted synthesis of nanometer- to micrometer-sized structures and plasma–particle interaction in nuclear fusion technology. More recently, with the ever-shrinking length scales in nanomanufacturing, using the surface-charge-driven interaction between contaminating nanoparticles and photon-induced plasmas may become the only route to effective nanoparticle contamination control.

Although it has drawn the attention of the entire research community, thus far the fundamental interaction between plasma and particles on the nm size scale has been largely unexplored. This is mostly because of the nonexistence of experimental data needed to verify the few modeling efforts available in the literature. The reason for this lack of experimental data for particles of nm length scales is that, currently, all experimental methods to obtain information about the particle charge—such as the particle resonance method, force-balancing, particle interactions with electric fields, and Mie ellipsometry and dust density waves analysis—are either directly or indirectly based on light scattering techniques, which face a substantial loss of signal-to-noise in the nm regime due to the sixth-power-dependence of the signal intensity on the particle size r (I ∝ r^-6).

In this Letter, we demonstrate that the interaction between plasma and nm-sized semiconductor quantum dots (QDs) is directly connected to and can be visualized by a change in their photoluminescence (PL) emission spectrum. This is done by bringing an electrically floated QD-deposited sample into contact with a low pressure argon plasma and monitoring the photoluminescence (PL) spectrum of the QDs in a time-resolved fashion before, during, and after plasma exposure.

QDs behave as zero-dimensional quantum wells for charge carriers. When these nanostructures are optically excited, an electron–hole pair is generated and confined in the quantum dot. This electron–hole pair relaxes back to the bound states in the quantum well and, finally, recombines. During the latter process, a photon with a well-defined energy is emitted. When considering an ensemble of...
quantum dots, this results in the emission of spectrally narrow-banded light, i.e., a photoluminescence peak. Essential in the method presented here is that the photoluminescence wavelength of the used QDs shifts due to the presence of excess charges and electric fields locally near their surface—a mechanism known as the quantum-confined Stark effect (QCSE).29,30

In our experiments, we used commercially available (from NanoOpticalMaterials) water-soluble CdSSe-ZnS gradient-alloyed shell QDs with an average PL emission peak of $540 \pm 10$ nm and a full-width-at-half-maximum of 34 nm. Their core radius and the shell thickness were 2.1 and 0.9 nm, respectively. The QD samples were prepared by diluting colloidal QDs in distilled water to a concentration of 2 mg/ml, drop-casting 10 $\mu$l of that dilution on a silicon substrate and letting the liquid evaporate after which the QDs remained on the substrate. The QD sample was clamped on a stainless-steel substrate holder, which was electrically insulated from the grounded walls. The QD sample, therefore, had a floating potential with respect to the plasma bulk. The photoluminescence emission upon laser excitation before, during, and after plasma exposure was recorded spectrally and temporally resolved with respective resolutions of 10 pm and 1.5 s. Figure 1 shows a schematic of the experimental configuration developed to achieve this.

The plasma discharge used for the exposure was driven by an RF generator set at a frequency of 13.56 MHz and an input RF power of 50 W. The axisymmetric circular RF electrode (12 cm in diameter) was mounted on top of the vacuum chamber. The chamber walls acted as a grounded counter electrode, which resulted in an asymmetric discharge. The vessel was equipped with a vacuum system, consisting of a prepump and a turbo-molecular pump, to achieve a base pressure of $10^{-4}$ Pa. Argon gas was fed into the chamber with a flow rate of 1 sccm, and the total gas pressure was kept constant for all measurements at 4 Pa.

The QDs were excited in situ using pulsed laser light with a wavelength of 405 nm, after which the photoluminescence emission of the QDs on the substrate was focused on the 250 $\mu$m entrance slit of a monochromator (Acton Research SpectraPro275). The spectrally separated light was then imaged by an intensified charge-coupled device (ICCD) camera (Andor iStar 334T) mounted on the exit slit of the monochromator. The output of the measurements is a time series of spectra. By applying the excitation laser in a pulsed manner, the experiment allowed for direct background correction and averaging.

Exemplary, Fig. 2 shows two photoluminescence spectra from the same QD sample before (blue) and during (red) plasma exposure. A total redshift of 0.15 nm of the PL spectrum was observed after 76.5 s of plasma exposure. From spectral PL curves as shown in this figure, the center wavelength of the PL peak was determined, by fitting the background-corrected data with an exponentially modified Gaussian fit function, with an accuracy of 0.02 nm.
Figure 3(a) shows the center wavelength of the PL peak and the PL peak intensity as a function of time before, during, and after exposure of the QD sample to the plasma. As can be seen immediately from this figure, the PL peak’s center wavelength responds to plasma impact on two distinctive timescales. On short timescales, an initial fast shift up to 0.04 nm within the first 1.5 s after the plasma was switched on is observed. On longer timescales, the center wavelength of the PL peak appears to shift slowly with time in the spectral domain over up to 0.11 nm during the remaining 75 s of plasma exposure. Moreover, the center wavelength of the PL peak appears to shift back in the opposite direction of the initial redshift immediately after switching off the plasma.

First, the long timescale drift of the center wavelength of the PL peak is mainly attributed to thermal effects of the plasma on the substrate and the QDs, which are in good thermal contact with it. It is expected that the temperature-induced enhancement of the lattice dilation and the interaction between excitons and phonons lead to the PL redshift.

We also measured the temperature of the QD sample during this plasma exposure [see Fig. 3(b)] and observed, on average, a redshift of 0.11 nm for an increase in 1.1 K in sample temperature during plasma exposure. This redshift in the PL wavelength of similar QDs due to increasing temperatures around ambient conditions has been well established in the literature and comparable to Refs. 32 and 33. We cross-checked this effect by externally heating the QD sample without applying plasma and recorded comparable redshifts (about 0.1 nm/K) of the center wavelength of the PL peak as a function of sample temperature [see Fig. S1(b) in the supplementary material]. From the results, it can be concluded that the substrate and the QDs follow the same temperature trend and, hence, good thermal contact between the substrate and QDs is in place. Otherwise, a limited thermal contact would have led the temperature of the QDs to rise disproportionately. It has been verified analytically that—even in the case of reduced thermal contact between the QDs and the substrate—upon sudden heating of single QDs by ion recombination events (occurring roughly 1.5 times each second), the internal QD temperature relaxes back to the substrate temperature on nanosecond (and shorter) timescales. This timescale is much shorter than the timescale of the measurements and, hence, the temperature induced due to direct plasma heating of the QDs is negligible compared to Stark shift caused by plasma charging effect.

Next to the wavelength shift, we also observed a decrease in the PL intensity during plasma exposure [red circles in Fig. 3(a)]. This is also mostly attributed to thermal effects. From the literature, it is well known that thermal activation of surface trapped states and increased nonradiative recombinations may lead to a decrease in PL intensity. We quantify this thermal effect on the PL intensity with the external heating to be \(-1.6\% / K\) [see Fig. S1(a) in the supplementary material]. This is in agreement with the literature values reporting a temperature-related PL intensity reduction of \(-1.6\% / K\), which was obtained for the heating of CdSe/ZnS QDs in poly(lauryl methacrylate) matrices.

The decrease in the PL intensity during plasma exposure is slightly higher, i.e., \(-1.9\% / K\). This difference is most likely due to ion-induced effects on the PL emission of the QDs, as we will explain below. The intensity largely recovers when the QDs cool down after plasma exposure, but not fully due to this additional ion-induced effect.

The plasma-enabled ion bombardment might partly sputter the ZnS shell, and therefore, the PL emission intensity may be reduced, being essentially a nonreversible effect. In theory, this could be a reason for the fact that the PL emission intensity reduction is not fully reversible in the case of 76.5 s plasma exposure. However, this effect cannot change the exciton localization and the PL wavelength; if the ion sputtering could impact until the CdSe core, quantum confinement would be lost and the specific QD would be expected to no longer contribute to the overall PL signal.

Another plasma-induced effect that can influence the PL properties of QDs is the incorporation of plasma ions in the QDs. Due to ion incorporation into the semiconductor lattice, point defects may possibly be introduced, consequently affecting the optical property of the semiconductor. These ion-induced defects can for instance serve as local nonradiative recombination centers for electron–hole pairs, reducing radiative lifetimes and the PL efficiency and intensity.

The above-mentioned effects may contribute to the “slow shift,” but their timescales (see the supplementary material) are too long to explain the initial “fast shift.” Figure 4 shows the time-resolved PL peak position of the QD samples for different plasma exposure times while all other plasma parameters were kept the same for these
Switching off the plasma [see Figs. 4(a) and 4(b)]. Moreover, only for long plasma exposures, there remains a small negligible for very short plasma exposures of 4.5 s [see Fig. 4(d)]. Therefore, the macroscopic electric field near the sample’s surface cannot directly explain the observed spectral fast shift.

The macroscopic electric field induces a surface charge on the substrate. This surface charge randomly fluctuates due to the discrete nature of the charging process. It can locally cause a larger microscopic electric field, which can induce a larger Stark shift. To evaluate this effect, we consider a spherical QD located on a Si substrate sensing a microscopic electric field caused by charges present on the substrate surface facing the plasma. The Stark shift due to the microscopic electric field (near the QD) induced by a certain quasi-static electron configuration on the surface is calculated using Eq. (1). Since the experimentally observed \( \Delta \lambda \) has been measured with the 750 ms exposure time, it is integrated over many quasi-static electron configurations as well as many photoluminescence lifetimes of the QDs. To account for this, we first calculate the spectral shift for each quasi-static electron configuration and then average the shift over all configurations.

The macroscopic electric field of 2.6 \( \times 10^5 \) V/m distributed over the substrate surface as 10\(^5\) random quasi-static electron configurations. The microscopic electric fields and their fluctuations calculated at the location of the QD (\( a = 2.1 \) nm) for each quasi-static electron configuration. The histogram of the microscopic electric field and the relevant Stark shift are shown in Fig. 5. The averaged shift is indicated as mean of the histogram, \( \delta_{\text{mean}} = \Delta \lambda (E_{\text{mac}}) = 0.015 \) nm [see Fig. 5(b)]. This shift is close to our observed fast redshift (0.04 nm). The difference may be explained by the influence of excess electrons trapped near the QD surface (1.5 nm), which is not involved in the calculation of the Stark shift in the above surface charge model. To account for this, we will evaluate the contribution of the QDs sensing the excess electrons trapped near their surface as follows.

The spectral fast shift appears to be an immediate result of direct plasma impact. Here, the QDs will undergo a redshift (\( \Delta \lambda \)) under the influence of the charges and electric fields locally near their surface due to the quantum-confined Stark effect. This redshift is expressed as:

\[
\Delta \lambda = 0.03 2^2 (\hbar c)^{-1} (m_\text{e}^* + m_\text{h}^*) \alpha (2\pi eE)^2 / h,
\]

where \( e, h, \alpha, m_\text{e}^*, \) and \( m_\text{h}^* \) indicate the elementary charge, Planck’s constant, the QD’s core radius, the electron’s effective mass, and the hole’s effective mass, respectively. In our situation, the observed Stark shift can be either due to excess charges trapped near the surface of the QDs and on the substrate surface, or due to plasma self-induced macroscopic electric fields present in the vicinity of the QDs.

First we consider the possible quantitative influence of the macroscopic electric field (\( E_{\text{mac}} \))—i.e., the plasma sheath electric fields—on the PL peak’s center wavelength of the QD. The estimated plasma-induced macroscopic electric field is approximately 2.6 \( \times 10^5 \) V/m at an electrically floating surface near an RF sheath edge under the current plasma conditions. This would lead to a Stark redshift of \( \delta_{\text{mac}} = \Delta \lambda (E_{\text{mac}}) = 7.2 \times 10^{-5} \) nm [Eq. (1)], much smaller than the observed fast redshift of 0.04 nm. To account for this, we will first calculate the spectral shift for each quasi-static electron configuration and then average the shift over all configurations.

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The charge on a spherical particle on a flat surface facing a plasma imposing an electric field \( E \) can be obtained from \( Q = (1.64)/(4\pi\epsilon_0)Er^2 \), with \( r \) being the particle radius, known as the “shared charge model.” Considering the macroscopic electric field of 2.6 \( \times 10^5 \) V/m, the calculated shared charge will be about 0.002 e. This means that on average 0.2% of QDs on the sample have one elementary charge near their surface, which we will refer to them as charged QDs. According to the results of the quantum-confined Stark shift models, an electron trapped near the QD’s surface—the size and material as used in this work—would induce a redshift of 15 nm of the PL peak position. Considering the measured PL spectrum as the sum of both unshifted PL spectra emitted by uncharged QDs (most of the QDs in the population) and 15 nm redshifted spectra emitted by charged QDs (0.2% of the total QD population as explained above), the resulted Stark shift will be 0.02 nm, which is also in a good agreement with our observed fast redshift. However, the assumption of
charged and uncharged QDs on the surface is over-simplified. In reality, for instance, uncharged QDs in the neighborhood of charged QDs will also be influenced by Stark effects induced on longer length scales. From the analyses above, we can conclude that the observed fast redshift can be explained by the total Stark shift including both contributions: the 0.015 nm redshift due to the charges near the QDs on the substrate surface and the 0.02 nm redshift due to the charges attached to QDs under the current plasma conditions. With our technique, we were able to experimentally determine a Stark redshift of 0.04 nm of the PL peak center wavelength of the QDs. From such measurement, one could estimate for instant (plasma-induced) surface charges and the charge on nanoparticles on plasma-facing surfaces. It should be noted that the reported (Stark) redshift of the QDs’ PL is ascribed to the overall electric field of nearby electrons residing on the surface due to exposure to the plasma and not to direct incorporation of electrons into the QDs’ core.

In conclusion, we demonstrated that it is possible to directly detect plasma charging of nanometer-sized structures by measuring the time-dependent, charge-induced, spectrally shifted photoluminescence signal emitted by QDs on an electrically floating substrate facing a plasma environment. We measured a total maximum spectral redshift of 0.15 nm with an accuracy of 0.02 nm and were able to differentiate between a direct plasma charging induced fast shift and a thermal- and ion-induced shift on longer timescales. Ultimately, the method introduced here may enable charge measurements of airborne QDs inside the plasma bulk volume, which could even be calibrated absolutely by applying laser-induced photodetachment and additional sensitive plasma diagnostics, such as microwave cavity resonance spectroscopy (MCRS).

The current work and the method it introduces allow the research community to shine light on the most fundamental processes regarding the charge collection of micro- and nanostructures in various fields, ranging from complex and dusty plasma physics to aerosol science and astrophysics.

See the supplementary material for the thermal-induced PL redshift of externally heated QDs and the plasma ion-induced effects on PL spectra of QDs.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

1. T. W. Hartquist, O. Havnes, and G. E. Morfill, “The effects of charged dust on Saturn’s rings,” Astron. Geophys. 44, 5.26–5.30 (2003).
2. C. Goertz and O. Havnes, “Electrostatic forces in planetary rings,” Geophys. Res. Lett. 15, 84–87, https://doi.org/10.1029/GL015i001p00084 (1988).
3. H. Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Möhlmann, “Plasma crystal: Coulomb crystallization in a dusty plasma,” Phys. Rev. Lett. 73, 652–655 (1994).
4. M. Thoma, M. Kretschmer, H. Rothermel, H. Thomas, and G. Morfill, “The plasma crystal,” Am. J. Phys. 73, 420 (2005).
5. T. W. Hyde, J. Kong, and L. S. Matthews, “Helical structures in vertically aligned dust particle chains in a complex plasma,” Phys. Rev. E 87, 053106 (2013).
6. M. Pustylnik, M. Fink, V. Nosenko, T. Antonova, T. Hagl, H. Thomas, A. Zobnin, A. Lipaev, A. Usachev, V. Molotkov et al., “Plasmakristall-4: New complex (dusty) plasma laboratory on board the international space station,” Rev. Sci. Instrum. 87, 093505 (2016).
7. X. Wang, J. Schwam, H.-W. Hsu, E. Grüner, and M. Horányi, “Dust charging and transport on airless planetary bodies,” Geophys. Res. Lett. 43, 6103–6110, https://doi.org/10.1002/2016GL069491 (2016).
8. E. Rosenfeld and A. Zakharov, “Dust levitation above the lunar surface: Role of charge fluctuations,” arXiv:1706.09664 (2017).
9. B. Tadsen, F. Greiner, S. Groth, and A. Piel, “Self-excited dust-acoustic waves in an electron-depleted nanodusty plasma,” Phys. Plasmas 22, 113701 (2015).
10. M. J. H. van de Watering, S. Nijdam, J. Beckers, and G. M. W. Kroesen, “Void dynamics in low-pressure acetylene RF plasmas,” in APS Gaseous Electronics Conference (2013).
F. Greiner, A. Melzer, B. Tadens, S. Groth, C. Killer, F. Kirchsclager, F. Wieben, I. Pilch, H. Krüger, D. Block et al., "Diagnostics and characterization of nanodust and nanodusty plasmas," Eur. Phys. J. D. 72, 81 (2018).

M. Hundt, P. Saddler, I. Levchenko, M. Wolter, H. Kersten, and K. Ostrickov, "Real-time monitoring of nucleation-growth cycle of carbon nanoparticles in acetylene plasmas," J. Appl. Phys. 109, 123305 (2011).

B. Santos and F. Vidal, "Influence of multipolar electrostatic and van der Waals forces on the coagulation of silicon nanoparticles in low-temperature argon-silane plasmas," Plasma Sources Sci. Technol. 29, 115004 (2020).

M. Rubel, M. Cecconello, J. Malmberg, G. Sergenkon, W. Riel, J. R. Drake, A. Hedqvist, A. Huber, and V. Philippus, "Dust particles in controlled fusion devices: morphology, observations in the plasma and influence on the plasma performance," Nucl. Fusion 41, 1087 (2001).

J. Winter, "Dust in fusion devices: A multi-faced problem connecting high- and low-temperature plasma physics," Plasma Phys. Controlled Fusion 46, B583 (2004).

M. van de Kerkhof, A. M. Yakunin, V. Kvon, S. Cats, L. Heijmans, M. Chaudhuri, and D. Astakhov, "Plasma-assisted discharges and charging in EUV-induced plasma," J. Micro/Nanopatterning, Mater., Metrol. 20, 013801 (2021).

C. Cui and J. Goree, "Fluctuations of the charge on a dust grain in a plasma," IEEE Trans. Plasma Sci. 22, 151–158 (1994).

T. Matsoukas, M. Russell, and M. Smith, "Stochastic charge fluctuations in dusty plasmas," J. Vac. Sci. Technol. A 14, 624–630 (1996).

M. Mamunuru, R. L. Picard, Y. Sakiyama, and S. L. Girshick, "The existence of non-negatively charged dust particles in nonthermal plasmas," Plasma Chem. Plasma Process. 37, 701–715 (2017).

B. Santos, L. Cacot, C. Boucher, and F. Vidal, "Electrostatic enhancement factor for the coagulation of silicon nanoparticles in low-temperature plasmas," Plasma Sources Sci. Technol. 28, 045002 (2019).

A. Melzer, T. Trottenberg, and A. Piel, "Experimental determination of the charge on dust particles forming coulomb lattices," Phys. Lett. A 191, 301–308 (1994).

J. Carstensen, H. Jung, F. Greiner, and A. Piel, "Mass changes of microparticles in a plasma observed by a phase-resolved resonance method," Phys. Plasmas 18, 033701 (2011).

H. Jung, F. Greiner, O. H. Asnaz, J. Carstensen, and A. Piel, "Resonance methods for the characterization of dust particles in plasmas," J. Phys. Plasma 82, 615820301 (2016).

J. Carstensen, F. Greiner, D. Block, J. Schablinski, W. J. Miloch, and A. Piel, "Charging and coupling of a vertically aligned particle pair in the plasma sheath," Phys. Plasmas 19, 033702 (2012).

J. Carstensen, F. Greiner, B. Tadens, J. Schablinski, W. J. Miloch, and A. Piel, "Charging of micro-particles in a low pressure spatial plasma afterglow," J. Phys. D 52, 322003 (2019).

B. Tadens, F. Greiner, and A. Piel, "On the amplitude of dust-density waves in inhomogeneous dusty plasmas," Phys. Plasmas 24, 033704 (2017).

A. Melzer, H. Krüger, S. Schütt, and M. Mulsow, "Dust-density waves in radio-frequency discharges under magnetic fields," Phys. Plasmas 27, 033704 (2020).

J. Seufert, M. Rambach, G. Bacher, A. Forchel, T. Passow, and D. Hommel, "Single-electron charging of a self-assembled II–VI quantum dot," Appl. Phys. Lett. 82, 3946–3948 (2003).

K. Park, Z. Deutsch, J. J. Li, D. Oron, and S. Weiss, "Single molecule quantum-confined Stark effect measurements of semiconductor nanoparticles at room temperature," ACS Nano 6, 10013–10023 (2012).

Y. P. Varshini, "Temperature dependence of the energy gap in semiconductors," Physica 34, 149–154 (1967).

D. Valerini, A. Creti, M. Lomascolo, L. Mannu, R. Cingolani, and M. Anni, "Temperature dependence of the photoluminescence properties of colloidal CdSe/ZnSe core/shell quantum dots embedded in a polystyrene matrix," Phys. Rev. B 71, 235409 (2005).

G. W. Walker, V. C. Sundar, C. M. Rudzinski, A. W. Wun, M. G. Baswendi, and D. G. Nocera, "Quantum-dot optical temperature probes," Appl. Phys. Lett. 83, 3553–3557 (2003).

W. Schoenfeld, C. H. Chen, P. Petroff, and E. Hui, "Argon ion damage in self-assembled quantum dots structures," Appl. Phys. Lett. 73, 2935–2937 (1998).

A. Ekinov, A. I. Efros, T. Shubina, and A. Skvortsov, "Quantum-size Stark effect in semiconductor microcrystals," J. Lumin. 46, 97–100 (1990).

J. Seufert, M. Obert, M. Scheibner, N. Gippius, G. Bacher, A. Forchel, T. Passow, K. Leonardi, and D. Hommel, "Stark effect and polarization in a single CdSe/ZnSe quantum dot," Appl. Phys. Lett. 79, 1033–1035 (2001).

S. E. Yalcin, J. A. Labastide, D. L. Sowle, and M. D. Barnes, "Spectral properties of multiply charged semiconductor quantum dots," Nano Lett. 11, 4425–4430 (2011).

E. Barnat and G. Hehnert, "Electric field profiles around an electrical probe immersed in a plasma," J. Appl. Phys. 101, 013306 (2007).

D. Kim and D. J. Economou, "Simulation of a two-dimensional sheath over a flat wall with an insulator/conductor interface exposed to a high density plasma," J. Appl. Phys. 94, 2852–2857 (2003).

T. Sheridan and A. Hayes, "Charge fluctuations for particles on a surface exposed to plasma," Appl. Phys. Lett. 98, 091501 (2011).

L. Heijmans and S. Nijdam, "Dust on a surface in a plasma: A charge management," Phys. Plasmas 23, 043703 (2016).

Y. Wang, J. Colwell, M. Horanyi, and S. Robertson, "Charge of dust on surfaces in plasma," IEEE Trans. Plasma Sci. 35, 271–279 (2007).

M. Hasani, Z. Marvi, and J. Beckers, "Probing negative ions and electrons in the afterglow of a low power oxygen radiofrequency plasma using laser-induced photodetachment," J. Phys. D 54, 495202 (2021).

J. Beckers, F. Van De Wetering, B. Platier, M. Van Nhuijs, G. Brussaard, V. Banine, and O. Luiten, "Mapping electron dynamics in highly transient EUV photon-induced plasmas: A novel diagnostic approach using multi-mode microwave cavity resonance spectroscopy," J. Phys. D 52, 034004 (2019).

B. Platier, T. Staps, M. van der Schans, W. Ifzerman, and J. Beckers, "Resonant microwaves probing the spatial afterglow of an RF plasma jet," Appl. Phys. Lett. 115, 254103 (2019).