DUST PARTICLE DIAGNOSTICS IN RF PLASMA DEPOSITION OF SILICON AND SILICON OXIDE FILMS (INVITED)

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ABSTRACT

Particle contamination formed in reactive plasmas imposes an upper limit on the rate for particle-free deposition. Conversely, these plasmas could be exploited to produce nanometric clusters and particles for various applications. Infrared absorption spectroscopy has been applied to analyse the chemical composition of suspended particles. Mass spectrometry was also used to investigate cluster formation in these deposition plasmas. In pure silane plasmas, a random model reproduces the measured mass spectra, whereas the rich plasma chemistry in silane/oxygen mixtures shows a remarkable tendency to produce silasesquioxane anions.

INTRODUCTION

Plasma-enhanced chemical vapour deposition of silicon and silicon oxide has widespread commercial applications for solar cells, thin film transistors and microelectronics. Particles formed during silane plasma processing by plasma state polymerisation are a source of contamination [1,2]. They are negatively-charged due to electron-ion flux equilibration at their surface and so are trapped by the plasma sheath potentials and accumulate in electrostatic suspension between the electrodes. If particles are incorporated in the film, they can cause structure defects [3]. Damage can still occur even if the particles never reach the substrate, since powder clouds suspended in the plasma above the growing film can cause inhomogeneous deposition by locally changing the plasma power dissipation, electron density and energy distribution.

In this paper, we investigate deposition uniformity, particle composition by infrared absorption spectroscopy, and the initial molecular precursors by mass spectrometry in low pressure RF capacitive discharges.

NON-UNIFORM DEPOSITION DUE TO POWDER SUSPENDED IN THE PLASMA

The plasma box reactor (Fig. 1) investigated consists of a rectangular RF electrode suspended inside a grounded reactor box. The process gases are introduced through a showerhead incorporated in the RF electrode and residual gases are pumped out of the back wall designed as a coarse grid. The reactor was heated uniformly to a temperature of 200 °C. The plasma cross-section can be viewed through a front window, and windows are also installed on the reactor sides at the end of 10 cm-long tubes to prevent deposition problems, with grids placed at the reactor wall to preserve electrical continuity. Beam-expanded polarised light from an Argon ion laser is scattered from particles and monitored by a CCD camera. The plasma emission background was eliminated by using a 488 nm interference filter. For this study, the scattered intensity was simply used as an indicator for the powder quantity. The overall film uniformity was measured *ex situ* by interferograms obtained by illuminating the substrate with a homogenous white light source and recording the transmitted light through a 700 nm interference filter. Each interference fringe indicates a 80 nm change in the film thickness.

Results

First of all, extraneous causes of film non-uniformity were avoided, such as non-uniform electrode voltage [4], poor substrate contact with the electrode [5], and inappropriate gas flow distribution (a uniform gas showerhead is necessary for depositing uniform films in this configuration).

Figure 1. a) Top and b) front view of the laboratory plasma reactor

Film a) in Fig. 2 deposited at low input power shows a very good uniformity but at a low deposition rate of $1.5 \text{ \AA/s}$. In contrast, film b) deposited at higher input power with powder formation has a deposition rate of $3.4 \text{ \AA/s}$, with a strongly degraded uniformity. The inhomogeneities are concentrated at the edges of the substrate where the thickness increases rapidly over the last 3 cm. The scattered intensity profiles show clear differences with and without substrate: it would appear that the substrate greatly influences the powder traps. The regions above the substrate where the scattered intensity is higher correspond to regions where the film thickness is also thicker. This shows that inhomogeneous powder distribution gives a non-uniform film thickness.

a) power = 50 W

b) power = 100 W

Figure 2. Global interferograms for films deposited a) at 50 W (no powder observed); and b) 100 W input power (with powder). The thickness profile corresponds to film b) along the line shown. Curve A represents the vertically-integrated intensity scattered from the powder measured from the CCD image shown; curve B is for the case without substrate.

Fig. 3 Interferograms of amorphous silicon films deposited at 13.56 MHz; the deposition conditions are identical to Fig. 2 b) except for a glass frame placed around the substrate. Curve A corresponds to the scattered intensity profile with the additional substrate strips and curve B to the case with the substrate alone.

In a second experiment, the substrate was surrounded by strips of substrate in order to cover the whole of the bottom area of the ground electrode. The film obtained in this configuration had good homogeneity even at elevated deposition rates ($3.6 \text{ \AA/s}$) since the inhomogeneities were completely confined to the substrate strips. The additional pieces of substrate displace the powder traps that appear at the transition between the substrate and the electrode. This is not a trivial result, because if the powder location were determined purely by fringing electric fields at the reactor edge, then the dielectric inserts would have no effect. Moreover, a 3 mm gap between a glass plate and the substrate reintroduced thickness gradients on the substrate. Geha *et al* [6] have also demonstrated the use of dielectric inserts to 'tune' the plasma potential in order to reduce particle trapping. The displacement of the powder clouds may be due to a shift in plasma potential wells, or to thermophoretic forces [7] which would arise if the dielectric surfaces were heated by the plasma (by ion bombardment) above the temperature of the surrounding metallic electrodes. The step in the electrode surface at the substrate edge has no influence because metal frames of the same thickness as the glass did not change the powder distribution. These observations suggest that a well-designed dielectric matching across the substrate-electrode boundary greatly improves deposition uniformity. A practical implementation would be to embed alumina shims in the ground electrode at the substrate perimeter so that the flat electrode profile would not hamper robotic manipulation of the substrates.

IN SITU PARTICLE DIAGNOSTICS BY INFRARED ABSORPTION SPECTROSCOPY

Powder formation can be observed in industrial processing of thin film SiO_x but there is only scarce information on particulates, for example, in HMDSO (hexamethyldisiloxane) RF plasmas. Diagnostics are required to understand the plasma physics and chemistry and to optimize the deposition quality. The aim here is to characterize HMDSO plasmas by in situ Fourier transform (FTIR) infrared absorption spectroscopy. Silicon oxide particle production has been similarly investigated for silane/oxygen plasmas [8].

Experiments were performed in a small, capacitively-coupled RF plasma reactor operating at 13.56 MHz [8]. These experiments were performed with reactor and electrodes at room temperature and at a pressure of 0.8 mbar. Typical flow rates were 8 sccm HMDSO, 80 sccm oxygen and 10 sccm helium. Infrared absorption spectroscopy was performed using a commercial FTIR instrument (Bruker Equinox). The infrared beam leaving the spectrometer was directed through ZnSe windows and the plasma (single pass) and focused by an off-axis paraboloid gold mirror onto a cooled mercury-cadmium-telluride detector. Transmission spectra were recorded in the range $700\text{--}4000 \text{ cm}^{-1}$ with a resolution of 1 cm^{-1} and an acquisition rate of up to 100 kHz, with averaging of up to five hundred spectra. To minimize atmospheric absorption bands, the infrared

Figure 4. Absorbance spectrum of plasma-produced components for a HMDSO / oxygen mixture.

light path was enclosed and continuously flushed with dry nitrogen. Transmission reference spectra in vacuum were acquired before and after each measurement to check for possible influences of deposited layers on the windows and variations in the detector sensitivity and source. The HMDSO gas background absorbance in Fig. 4 was removed by defining the absorbance as $-\ln[T(\text{plasma})/T(\text{gas})]$, where the gas transmission spectrum was corrected for plasma depletion [9] (85% depletion in this case). Well-defined absorption peaks indicate production of various infrared active gases whereas the broad structure in the region 1000 cm^{-1} to 1280 cm^{-1} is from solid SiO_x particles within the plasma. The width of this absorption band is due to the stretch vibration of Si-O-Si linkage in the particles. The lines at 844 and 1263 cm^{-1} originate from the rocking and stretch vibrations respectively of $\text{Si}-(\text{CH}_3)_n$, ($n < 3$). The lines at 2913 and 2966 cm^{-1} originate from the asymmetric and symmetric stretch vibrations of CH_3 . Based on the fact that the absorption lines of the HMDSO molecules are completely eliminated by the gas background correction, the remaining $\text{Si}-(\text{CH}_3)_n$ and CH_3 absorption suggest the presence of carbon compounds within the particles. In higher diluted HMDSO plasma, typically for flux ratio $[\text{O}_2]:[\text{HMDSO}] > 40$, these absorption peaks disappear suggesting that only little carbon is then included in the SiO_x particles. The lines at 2140 and 2340 cm^{-1} represent the gas phase stretch vibrations of CO and CO_2 respectively, whereas the absorption line at 1780 cm^{-1} is most probably due to the $\text{C}=\text{O}$ stretching in an aldehyde type molecule ($\text{R}-\text{COH}$), where the radical R is presumably $\text{Si}-\text{CH}_2$ or CH_3 . These measurements show that in the deposition of SiO_x with HMDSO, a fraction of the excess carbon is transported out of the reactor by the infrared active species CO , CO_2 and by aldehyde formation. Creation of these molecules could be either in the plasma via carbon-oxygen reactions, which supposes a fairly high fragmentation of the HMDSO molecule (because there are no C-O bonds in HMDSO) or from plasma-surface reactions such as oxygen etching of carbon in the deposited film.

Particle Size and Number Density Estimation using Infrared Absorbance and Rayleigh Scattering

In the absorbance spectrum of Fig. 5a) the large deviation from the base line is due to elastic scattering on the nanometer sized particles suspended in the plasma. The absorbance of the infrared beam is given by $C_{\text{ext}} N D$ where C_{ext} is the total extinction cross section, N the particle number density and D the optical path length within the plasma.

The total extinction (C_{ext}) of the infrared beam crossing the plasma is the sum of two contributions: The absorption part, in our case the Si-O-Si vibrations at 1000 cm^{-1} (C_{abs}), and the light scattering part (C_{sca}) from the particles in the plasma. Neglecting multiple scattering and assuming spherical particles, the scattering and absorption cross sections can be calculated from Mie theory using optical constants for appropriate materials ($\alpha\text{-SiO}$, $\alpha\text{-SiO}_2$, c-SiO_2). Fig. 5a) shows the comparison between the measured plasma absorbance for a highly concentrated HMDSO plasma (10 sccm HMDSO, O_2 and He at 0.1 mbar) and the calculated contributions of absorption and light scattering, assuming $\alpha\text{-SiO}$ particles with a radius R of 300 nm and number density $N = 5 \cdot 10^{12}\text{ m}^{-3}$. The cross sections C_{sca} and C_{abs} are given by the Rayleigh approximation [10] for particles small with respect to the infrared wavelength (2 to $20\text{ }\mu\text{m}$); this is more readily

Figure 5. a) Measured spectrum and calculated absorption and scattering of a low-dilution HMDSO plasma (10 sccm of HMDSO, oxygen and helium at 0.1 mbar and 40 W); b) Particle size and number density determination.

satisfied using infrared than visible light, but the low scattering intensity means that the method is only practicable for relatively large amounts of particles. Figure 5b) shows the resulting particle number densities in fitting the measured absorption and scattering for different particle sizes. The estimation of the particle size and particle number density used in Fig. 5a) was obtained from the intersection of the two curves.

MASS SPECTROSCOPY OF CLUSTERS AND PARTICLE PRECURSORS

To eliminate particles it suffices to prevent the formation of particle precursors. Quadrupole mass spectrometry of neutrals, cations and anions in a RF silane plasma has been used to assess their rôles in particle formation. The reactor [8] was the same as the one used for the FTIR experiments. A Balzers Plasma Process Monitor type PPM 421, comprising a double-focussing cylindrical mirror energy analyser and quadrupole mass filter, was used to detect neutral radicals and ions (positive and negative) with a mass range up to 2000 amu. The probe head, with 0.1 mm diameter extraction orifice, was positioned adjacent to the electrode gap at 10 mm from the plasma boundary. The question of non-perturbative anionic cluster sampling is addressed in Ref. [11].

Cluster Structure in Pure Silane Plasmas: Figures 6a) to 6c)

Figs. 6a) and 6c) show the negative and positive ion mass spectra measured in a low power, low pressure silane plasma. The anions are much heavier than the observed positive or neutral counterparts for these plasma parameters [8,11]. Anions with $n \leq 4$ (Fig. 6a)) present a clear maximum abundance for $\text{Si}_n\text{H}_{2n+1}^-$ whereas anions with five silicon atoms (to a lesser extent, six silicon atoms, similarly to cations in [12]) have particularly-abundant pure silicon clusters Si_5^- as well as Si_5H^- . Heavier clusters in Fig. 6a) exhibit a broad intensity distribution with respect to H-content. The featureless mass spectra indicate an absence of preferentially-abundant configurations for Si:H anions or cations, and a random bond model [13] can adequately describe the observed abundances of silicon and hydrogen in the clusters. The [H]:[Si] ratio of 4/3 within the anions [11] shows that cluster growth involves hydrogen depletion. If we assume sequential reactions with silane such as:

ie exclusively H_2 elimination, we obtain the ratio $[\text{H}]:[\text{Si}] = (2n+1)/n$ as observed at low masses [11,14]. If two hydrogen molecules can also be eliminated for reactions at higher masses, we can introduce f as the branching ratio for single H_2 elimination and hence $(1-f)$ is the branching ratio for double H_2 elimination. Therefore, for n consecutive reactions with silane molecules, n silicon atoms and $2fn$ hydrogen atoms are added to the cluster. The ratio $[\text{H}]:[\text{Si}]$ after a large number of consecutive silane reactions therefore tends to $2f$. The experimentally-observed $[\text{H}]:[\text{Si}]$ ratio is 4/3

Figure 6 Mass spectra for 25 to 237 amu with approximately unit mass resolution for a modulated plasma. The ordinate units are in counts per second. a) and b) show the negative ion measurements and model for silane plasma; c) represents the positive ions in silane plasma; d) and e) represent the negative and positive ions for 10% oxygen-in-silane plasma respectively; f) shows a comparison between a model and the positive ion mass spectrum in e), iterated from the mass group 90 to 102 amu.

Figure 6 contd. The same mass spectra a) to f), for masses 238 amu to 450 amu. The gases used were a 30 sccm flow of pure silane, or 10% oxygen-in-silane, at 0.1 mbar pressure. The grounded electrode was heated to 200°C. The RF power ($\sim 0.03 \text{ W cm}^{-3}$), at an excitation frequency of 13.56 MHz, was ON/OFF modulated at kHz frequencies so that negative ions could diffuse out from the plasma for detection [9,13].

and therefore the branching ratios of the H_2 and $2H_2$ elimination reactions are $f = 2/3$ and $1-f = 1/3$ respectively, ie 2:1. Sequential convolution of these reactions with these branching probabilities, starting from the measured abundances of the $Si_7H_x^-$ group to avoid undue bias from the chemical structure of the smaller ion clusters [8], gives the calculated negative ion mass spectrum in Fig. 6b) in which the isotopic abundances of silicon and oxygen have also been taken into account. Since polynomial multiplication is equivalent to convolution, iterated convolution of the silane reactions gives the same result as the binomial distribution approach used in [13].

Cluster Structure in Silane/Oxygen Plasmas: Figures 6d) to 6f)

In Figs. 6a) and 6c) only Si:H bonding can occur whereas in Figs. 6d) and 6e), intermediate groups ascribed to Si:H:O appear. The rich variety of Si:O:H radical chemistry completely changes the regular structured mass spectra of anions in pure silane plasmas and every single atomic mass unit is represented in silane/oxygen plasmas from 100 amu up to at least 1000 amu. The presence of special high-abundance anions indicates clusters with particular stability (discussed below). However, the regular structure of the cation spectrum (Fig. 6e)) shows no preferential configuration, similarly to the anions and cations in pure silane.

Mandich and Reents [15] have shown that H_2O addition promotes positive ion clustering in silane plasmas, and the extension of the cation mass spectrum in Fig. 6c) to Fig. 6e) on adding 10% oxygen to silane is consistent with their conclusions. The pure silane model based on single and double hydrogen molecule elimination was extended to include alternate reactions for oxygen addition [8]. A 2:1 branching ratio for H_2 and $2H_2$ elimination was also supposed for the oxygen addition reactions. As for the anion model above, convolution starting from the $Si_2H_xO_2^+$ abundances gives the calculated positive ion mass spectrum in figure 6f). Elimination only of molecular hydrogen means that a sequence of 'odd' masses develops independently of an 'even' mass sequence [8], which is borne out by the measurements in Fig. 6e). Comparing Figs. 6e) and 6f), the overall features of the cation mass spectrum are reproduced by the model, which retrospectively supports the choice of equal branching ratios between the H_2 and $2H_2$ elimination reactions for addition of silicon and oxygen. The reasonable agreement obtained lends support to the assumed iterative reaction sequence scheme which is essentially a statistical model for cluster growth.

Judging by the complexity of the negative ion spectrum for silane/oxygen plasmas in Fig. 6d) additional reaction mechanisms must also be involved. In fact, the observed high-abundance mass numbers (such as 319, 425, 531, 637 amu) correspond, plus one supplementary mass unit, to hydrosilasesquioxanes (that is, $H_{2n}Si_{2n}O_{3n}$, $n = 3, 4, 5, 6$) with increments of $SiOH_2$ (46 amu) and other small molecular fragments. The growth model for cations in Fig. 6f) assumed alternate addition of Si and O to the clusters and so imposes equal stoichiometry, but a model which accounts for silasesquioxane anions would require additional reaction schemes. Silasesquioxanes have exceptionally-stable cage structures which resist fragmentation and are passive to transformation by further growth [16]. If this is the reason for their enhanced abundance, then we can understand the presence of silasesquioxane anions by the trapping and longer lifetime of anions in a plasma [11]. Conversely, the absence of 'magic numbers' amongst the Si:O:H cations may be because these species are evacuated across the plasma sheath and so do not have time to accumulate particularly stable forms. In contrast to the silasesquioxanes, none of the Si:H cage-like cluster structures proposed by Martin and Schaber [17] are observed for anions or cations in pure silane.

Cluster Structure in Silane/Argon Plasmas

Different plasma conditions would change the branching ratio of H_2 and $2H_2$ elimination reactions and thereby control the composition and structure of the clusters. For example, argon-diluted RF plasmas show a higher component of silicon-rich clusters which are more strongly hydrogen depleted [18]. Noble gases play an active rôle, for example, via metastable processes [19] (Penning ionisation and dissociation) and their reactive ions (which have halogenic electronic structure): noble gases in plasmas are not simple 'buffer' gases. Kessels *et al* [20], in very different conditions of an argon-hydrogen-silane plasma expanding from a cascaded arc, find Si:H cations with a strong bias towards almost pure, dehydrogenated Si_n^+ clusters; these correspond to the nearly-pure Si:H cluster form in Ref. [12]. Following the above approach [8], the elimination

of 2H_2 is estimated in [20] to be more than an order of magnitude more probable than the elimination of H_2 - a strong reversal compared with the RF plasma results above - which is attributed to the higher gas temperature in the expanding plasma experiment.

Mass Discrimination in Quadrupole Mass Spectrometry

For a meaningful interpretation of the mass spectra, the relative sensitivity of the mass spectrometer to ions of different charge types (+/- neutral) and masses must be considered.

Charge-Sign-Independent Mass Discrimination: For quadrupole mass filters, as the mass resolution $M/\Delta M$ is increased, the transmittance T decreases; in theory, $T \propto \Delta M/M$. For a mass scan with fixed mass width, the transmittance therefore decreases with mass, theoretically $T \propto 1/M$ - this represents a discrimination against higher masses. In practice, the mass resolution and transmittance depend sensitively on the locus of the operating line in the Mathieu diagram determined by the quadrupole RF and DC voltages [21]. The real mass dependence of the quadrupole transmittance for the conditions used in Fig. 6 was experimentally estimated by comparison with the integral mode (DC voltage = 0 V) which acts as a high pass mass filter having 100 % transmission [22]; the measured mass discrimination was weak over the whole mass range shown. There remains the mass discrimination against heavy positive ions due to the velocity threshold effect at the first dynode (see following), although the 3.5 kV voltage used appeared sufficient for the high masses produced by silane/oxygen plasmas (Fig. 6d)).

Charge-Sign-Dependent Mass Discrimination: A series of experimental results suggest the rôle of anions in particle formation in low power, pure silane plasmas [11,23]. However, it is necessary to know if the negative ions exist alone as heavy species, or if they are i) in a continual cycling of attachment/detachment with equivalent-mass neutrals, or ii) merely a by-product of attachment to equivalent-mass neutrals in the decaying afterglow. Part of the evidence is the non-observation of heavy neutrals by conventional electron-impact ionisation. There are two possibilities of charge-sign-dependent discrimination against heavy neutral detection: **Cross-section:** Inefficient electron impact ionisation of neutral clusters (due to redistribution of energy amongst internal modes); and **Detection Efficiency:** Inefficient secondary-electron emission by large positive ions on impact at the channeltron first dynode (because of a velocity threshold for kinetic emission [24] which means that heavy cations, accelerated by the same potential as light cations, will not reach sufficient velocity for secondary electron emission). In contrast, the first electron on impact of a large anion may come directly via detachment from the anion itself [25] as opposed to Auger electron emission processes. Nevertheless, our characterisation of the first dynode potential effects using silane anions and cations shows that the charge sign discrimination is not strong for silane ions. Finally, we note that any mass discrimination effects would imply that heavy ionic clusters are even more abundant than shown in Fig. 6.

Attachment mass spectroscopy [26], whereby neutrals are converted to anions by electrons of a few eV rather than ionised at 70 eV, could be expected to enhance sensitivity compared with electron impact ionisation and probably cause less fragmentation due to the lower electron energy. However, the small, resonant cross-sections for attachment compared to ionisation meant that very high mass neutrals were still not detectable even by attachment mass spectroscopy using a Hidden plasma monitor (Fig. 7).

Figure 7. Electron attachment mass spectroscopy a) to silane, showing the anions produced in decreasing order from SiH_3^- ; and b) to polysilane groups. The ordinate axes are in counts per sec.

COAGULATION MECHANISMS IN COLLOIDAL PLASMAS

Extensive investigations have been made in order to identify the powder precursors and the gas phase reactions leading from the silane feed gas (SiH_4) to particulates, involving neutrals [27,28], positive ions and negative ions [14,23,29]. Powder formation in reactive plasmas can be considered as a two-phase colloid, in many respects similar to solid/gas aerosols. The particle growth in a RF silane plasma has been simulated by supposing agglomeration of uncharged protoparticles and using a commonly-employed model in aerosol physics; the Brownian Free Molecular Coagulation model [30,31]. At present only a few attempts have been made to include charging into an agglomeration model. Many charging models of particles in a plasma are based on orbital motion limited probe theory based on the equality of the electron and ion current impinging on the particle. The statistically-fluctuating charge on particles as large as a few nm means that they could be considered as neutral [31]. Gas drag may then lead to large losses of these neutral or charge-fluctuating [32] particle precursors therefore inhibiting further growth. Furthermore, charge-fluctuating nanoparticles can leave even a continuous plasma and so can be co-deposited in amorphous silicon films [33,34]. These findings might lead to advanced materials of nanoparticles in a thin film matrix. On further growth, particulates of several 10's of nm or more are necessarily negatively charged in the plasma which would be expected to reduce the agglomeration rate and also influence the maximum particle size. In colloidal silica, a well-known system which can be compared with SiO_x plasma-produced particles, the particles aggregate spontaneously if no stabilization mechanisms are present. Electrostatic stabilization, dominant in plasmas, is based on the competition between electrostatic repulsion between charged particles and Van der Waal's attraction. The stability for the silica colloidal system is given in this case by the pH value, whereas in the plasma the individual charging of the particles accounts for the system stability.

Powder dynamics in dusty plasmas is governed by several forces acting on the particles, including gravity, electrostatic forces, gas drag, thermophoresis due to thermal gradients and plasma-induced ion drag. The collective behavior of the particle assembly depends critically on interparticle forces which again depend on particle charging. The parameter which is used to order the strength of the particle coupling is the Coulomb parameter Γ defined as the ratio of the electrostatic interaction energy to the particle kinetic energy [35]: $\Gamma = Q^2 / (4 \pi \epsilon_0 d_p k T_p)$, with d_p the interparticle distance, Q the particle charge and T_p the particle temperature. Despite particle sizes much smaller than typically used in plasma crystal experiments, the very high number density in processing plasmas often leads to a Coulomb parameter between the value for liquid ($\Gamma > 2$) and solid ($\Gamma > 170$). Illumination by a polarized expanded laser beam shows high contrast 'Mie interference fringes' demonstrating the existence of spatial particle size segregation and, therefore, interparticle coupling forces [36]. Collective phenomena such as observed in plasma crystal experiments might be useful to understand the complex powder dynamics in reactive plasmas.

CONCLUSIONS

Several particle diagnostics have been used in silane-containing plasmas to study the influence of particles on deposition uniformity, the composition of particles, and the formation of ionic clusters. *In situ* FTIR measurements, corrected for gas depletion, reveal gases and particles produced in the plasma. The Rayleigh approximation was applied to determine the particle radius and number density using the different radius dependence of absorption and scattering in the absorbance spectrum. Complex mass spectra were modelled by iterative convolution of hydrogen elimination reactions with suitably-chosen branching ratios. Silasesquioxane anions were abundantly formed in silane/oxygen plasmas. Powder formation in reactive plasmas can be considered using a two-phase colloid description, with the proviso that particle charging and interparticle forces within plasmas are accounted for.

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