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Effect of structured electrodes on heating and plasma uniformity in capacitive discharges

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Received 5 August 2013, in final form 30 September 2013
Published 26 November 2013
Online at stacks.iop.org/JPhysD/46/505202

Abstract
The effect of various structured (non-planar) electrode topologies, e.g. rectangular, rounded and triangular trenches, on the electron heating dynamics and ion density profile in capacitively coupled radio frequency plasmas is investigated experimentally and by an analytical model. The measurements are carried out in neon. 2D Phase resolved optical emission spectroscopy is utilized to study the dynamics of energetic electrons inside and outside these structures at the kinetic level. In the presence of structured electrodes, non-planar RF sheaths form and affect the electron heating dynamics. We observe a local agglomeration of energetic electrons above the structures. These electrons originate from sheath expansion heating. Inside the structures, opposite vertical sheaths cause a temporal confinement of electrons. Non-planar sheaths at the trench orifice cause convergent fluxes of energetic electrons. Also, the ionization and, as a consequence, the plasma density are modified by these effects. This is characterized by radially resolved Langmuir probe measurements and described by a diffusion model with localized sources. Subsequently, the control of the radial plasma density profile is demonstrated. Via customized electrode topologies, high plasma uniformity at specific pressures and heights above the electrode is achieved with the additional benefit of strong enhancement of the plasma density. (Some figures may appear in colour only in the online journal)

1. Introduction
Capacitively coupled radio frequency (CCRF) plasmas find a diverse use in science and industry. They are utilized in fundamental research and are routinely applied in plasma processing and fabrication. Common applications are dry etching and deposition processes [1]. Typical low-pressure CCRF plasmas (0.1–100 Pa) are generated in a parallel-plate configuration (interelectrode distance of the order 1–10 cm) within a vacuum chamber by applying an external voltage waveform (amplitude of the order of 100 V and excitation frequency of 1–100 MHz).

Compared to inductively coupled plasmas, the plasma density is relatively low (10^9–10^10 cm^-3). The plasma density profile strongly depends on the discharge chamber configuration. In the case of an asymmetric CCRF discharge and large electrode gap the plasma density profile is radially inhomogeneous and typically concave in shape, i.e. there is a maximum in the discharge centre. For applications, an increase in density is desirable to enhance productivity and a homogeneous density profile is desirable to improve processing uniformity.

Several solutions have been proposed to increase the plasma density, e.g. the utilization of magnetic fields [2–4], application of multiple frequencies [5, 6], or very high frequencies [7–9] and utilization of high secondary electron emission oxides [10–12]. These technologically demanding concepts cause new problems (e.g. the standing wave effect) [13, 14]. However, it was found that structured electrodes can lead to an enhanced plasma density [15–19]. Especially, multi-hole electrodes have been subject of intense research. This electrode topology is found to speed up deposition processes [20] and increase the plasma density [21–23] over a wide range of pressures compared to the parallel-plate configuration. This effect was also reported for a radially symmetric ring trench.
configuration [24]. The uniformity of thin film deposition was found to be increased by certain electrode topologies [25]. Also, a homogenization of the plasma density profile via rectangular (tapered) holes was reported [26, 27].

Most of these studies have been restricted to phenomenological investigations of the effects of complex electrode surface topologies without providing a detailed understanding of these effects based on an analysis of the electron heating dynamics governing plasma sustainment.

A variety of electron heating mechanisms in CCRF plasmas depending on gas pressure and RF voltage amplitude is known [28–35]. While (collisional) ohmic heating is dominant in high pressure plasmas, at low pressures the so-called stochastic heating of electrons is most significant [36–39]. The latter is an efficient collisionless heating mechanism arising from electron interaction with spatio-temporally inhomogeneous electric fields of the oscillating plasma boundary sheath [40–45]. Modulated with the motion of the plasma sheath edge, i.e. the applied voltage waveform, highly energetic electrons are periodically accelerated into the plasma bulk (sheath expansion heating), where they dissipate their energy in collisions [46]. If the electron mean free path is long enough, these electrons can interact with the opposite sheath and (bounce) resonance heating is observed [47–49].

If the ionization is dominated by electrons heated via sheath expansion or collapse, the discharge is operated in \( \alpha \)-mode. Discharge operation in the secondary electron dominated ionization regime, i.e. at high RF voltage amplitude and high pressure, is called \( \gamma \)-mode [28]. In strongly electronegative plasmas, ionization is dominated by electrons that are accelerated by drift and ambipolar electric fields in the plasma bulk region and at the sheath edges (\( \Omega \)-mode) [32, 33, 50–53].

Here, we perform detailed experimental investigations of the dynamics of highly energetic electrons and its consequences on the plasma density profile on the kinetic level. We present experimental evidence for spatially modified electron heating dynamics in a low-pressure CCRF plasma in the presence of structured electrodes responsible for both the enhancement and homogenization of the plasma density profile.

This article is organized as follows. In section 2, the experimental setup and the applied diagnostics are introduced. In section 3, the effect of structured electrodes is characterized by the results of 2D phase resolved optical emission spectroscopy (PROES) and Langmuir probe measurements. The observed plasma density profile is compared to an analytical diffusion model. The control of the radial plasma density profile via radially symmetric structures is demonstrated. A summary is given in section 4. The model is presented in detail in the appendix.

2. Setup

Measurements are performed in a modified gaseous electronics conference (GEC) reference cell. Its spatial dimensions and specifications are documented in [54, 55]. Figure 1 depicts the experimental setup of this work.

The grounded electrode consists of a 10 mm thick planar disc with 101 mm diameter attached to a rod, both made from stainless steel, and it is lowered into the chamber from the top flange. It is held in position via a vacuum proof threaded coupling, which also provides connection to electrical ground. This allows the electrode to be freely positioned in height above the powered electrode.

Here, we present measurements at various pressures. All measurements are carried out in pure neon (purity: 5.0), which is also used as a probe gas for PROES due to its favourable spectroscopic properties.

RF power is fed to the powered electrode via an automatic L-type matching network. To measure the voltage drop across the discharge, a high voltage probe is connected to the feed line of the powered electrode. The setup does not allow measurements directly at the powered electrode. As a consequence a voltage calibration is necessary [56]. In this work all measurements are performed at 13.56 MHz and at a fixed RF voltage amplitude of \( U_{RF} = 264 \pm 4 \) V. The discharge is geometrically asymmetric and a dc self-bias develops. It shows a slight dependence on gas pressure and is nearly independent of the structure type (variation is less than 3% within the pressure range). At 15 Pa a dc self-bias \( \eta \approx -250 \) V.
Table 1. Cross sections of the investigated linear trench structures.

<table>
<thead>
<tr>
<th>Sketch</th>
<th>Rectangular Trench</th>
<th>Rounded Trench</th>
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<tr>
<td>Orifice</td>
<td>10 mm wide</td>
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<tr>
<td>Sketch</td>
<td>Triangular Trench</td>
<td>Triangular Trench</td>
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<tr>
<td>Orifice</td>
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<td>Aperture angle</td>
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is measured. At lower pressures the DC self-bias becomes more positive ($\eta \approx -240$ V at 3.5 Pa). The total DC self-bias is approximately 90% of the applied RF amplitude.

In a GEC cell non-planar electrode topologies are realized by placing shaped metal pieces on top of the powered electrode. The outer shape of these pieces is cylindrical with the diameter $D = 101$ mm equal to the planar and circular electrode of the cell.

Linear trenches are formed by using two metal cylinder segments, as shown in table 1 and in figure 1(b). These trenches are defined by their depth and the shape of the trench wall. Different structure types with a height of 20 mm are investigated. The simplest structure is the rectangular trench with two opposite side walls. The trench walls are perpendicular to the original electrode surface which also forms the bottom of the trench. Triangular shaped trenches (with two different aperture angles of 90° and 53°) are also used. Their side walls merge at the ground of the trench to form a triangle. The aperture angle of the trench is determined by the structure height and the upper trench width. A rounded trench profile has been investigated, too. Here, the radius equals the structure height.

In the original GEC cell, the powered electrode is surrounded by an electrically grounded metal shield reaching to the vertical height of the electrode. In the case of structured electrodes, the powered surface area is increased by the (unshielded) lateral surface area of the cylinder segments used to realize the structures. Therefore, to ensure comparability, a metal full cylinder 20 mm in height is placed on top of the original powered electrode as a plane-parallel reference scenario.

Obviously, the interelectrode distance varies in transversal direction to the trench, i.e. it is different inside and outside the trench. We denote the distance between the trench bottom and the flat grounded electrode $d$. A modified interelectrode gap $d'$ is defined as the distance between the upper edge (planar part) of the structure and the grounded electrode. For shaped trench walls the interelectrode distance varies between $d'$ and $d''$. In this work the separation of the electrodes, which is the distance between the grounded electrode and the (powered) trench ground, is $d = 70$ mm, i.e. the distance between the grounded electrode and the upper planar surface area of the structured electrode is $d'' = 50$ mm.

Lastly, radially symmetric trench structures are investigated (see figure 2). This allows both a comparison with previous works [16] and the utilization of multi-ringed electrodes to enhance the uniformity of the plasma density profile [24]. The trench depth is 10 mm, the form is square or rectangular, respectively.

2D PROES with the line of sight along the trench structures of the modified powered electrode is performed to gain lateral access to the dynamics of highly energetic electrons inside and outside the trench [57–59]. The utilized Andor iStar camera is synchronized with the RF generator and has a gate width, i.e. a temporal resolution, of $\Delta t = 5$ ns. Therefore, one RF cycle of the applied voltage waveform with period $T = 73.7$ ns is resolved in 15 snapshots. The absolute value of the phase between the applied RF voltage and the PROES data is estimated with an error of 5 ns, i.e. one gate width. From the observed emission, the excitation is obtained using a collisional–radiative model [60].

The plasma density is measured radially resolved at a height of 20 mm above the top surface of the structure by an RF compensated Langmuir probe (Scientific Instruments Smart Probe). Its tungsten wire tip is 10 mm in length and has a diameter of 0.15 mm. In the longitudinal configuration (compare figure 1(b)) both the probe and the PROES camera are aligned parallel to the trench. By rearranging the metal cylinder segments (axial rotation by 90°) measurements can be taken transversally to the trench structure. The plasma density is obtained from the ion saturation current [61].

3. Results

3.1. Electron heating dynamics

Figure 3 depicts the 2D spatio-temporally resolved excitation dynamics for different electrode topologies at 10 Pa neon gas pressure, 264 V RF voltage amplitude, and an interelectrode distance $d' = 50$ mm. Time evolves along the horizontal axis, the structure is varied on the vertical axis. Additionally, the first row depicts the applied RF voltage (red dot). Only 5 of the 15 snapshots within one RF period are shown, because special emphasis is put on the electron dynamics during the expansion phase of the sheath at the powered electrode. No relevant excitation processes are observed during the rest of the RF period at the powered electrode (compare figures 5 and 6). Therefore, one third of the RF cycle is shown here starting approximately from sheath collapse and covering the major part of the expansion phase at the powered electrode. The motion of the sheath edge adjacent to the powered electrode is phase shifted to that at the grounded electrode by 180° [62]. However, no pronounced sheath dynamics is observed at the (upper) grounded electrode in the second half of the RF period due to the strong asymmetry of the discharge. Additional data (and video material) depicting the spatio-temporal evolution of the excitation dynamics as a function of pressure and interelectrode distance and depicting the density profile is available online [63]. In the background the flange through which the Langmuir probe is inserted into the vacuum chamber is visible as a faint circular structure close to the centre of the graphs. Inside the sheath, excitation processes are weak. The dynamics at the RF sheath edge can be observed qualitatively in the image series. For all structures the excitation dynamics is dominated by sheath expansion heating. In the presence of a complex electrode topology specific features are observed.

Non-planar RF plasma sheaths form [18, 19] and a strong enhancement of the excitation rate localized within a structure
Figure 2. (a) Geometry of a single-ring trenched electrode. (b) Geometry of the double-ringed structure. The outer ring has a width $W_1 = 10$ mm, the inner ring $W_2 = 5$ mm.

Figure 3. Spatio-temporally resolved excitation rate in arbitrary units into Ne 2p$_1$ during the expansion phase of the sheath at the powered electrode for different electrode topologies. The gas pressure is 10 Pa. The circular structure in the centre of all figures results from a flange at the far end of the cell. The first row depicts the applied RF voltage (red dot).

and at its orifice is observed. It is assumed that the maximum of the excitation rate is caused by the convergence of electron fluxes due to cross-firing of electron beams accelerated by the sheaths in front of tilted trench walls plus contributions from electrons accelerated out of the trench by the vertically expanding sheath from the trench ground.

A comparison shows that the maximum of the excitation shifts in its vertical position to lower heights as the aperture angle increases. For the rectangular trench the maximum is located above the edge of the structure; for the 53° triangular trench it is located at the structure edge. In the case of a 90° triangular trench, a large fraction of the excitation caused by a cross-firing of highly energetic electrons is located within the structure. Ultimately, however, the electrons are accelerated out of the trench by interaction with the sheath expanding from the trench ground and a beam of highly energetic electrons propagates into the plasma bulk.

For the example of a rectangular trench, the mechanism of enhanced electron heating within the structure is illustrated in figure 4. The sheath and electron dynamics within the
Figure 4. Sheath and electron dynamics within the trench during the expansion phase obtained from the excitation rate into Ne 2p1 given in arbitrary units. The gas pressure is 10 Pa.

Figure 5. Excitation rate into Ne 2p1 for the rectangular trench at 10 Pa. The plot depicts the vertical dynamics inside and above the trench (binning: 4 mm). The trench height is marked by the black dashed line. The yellow dashed line marks the maximum sheath width. A beam of energetic electrons is indicated by the black dashed arrow.

Figure 6. Excitation rate into Ne 2p1 for the triangular trench (90°) at 10 Pa. The plot depicts the vertical dynamics inside and above the trench (binning: 4 mm). The trench height is marked by the black dashed line. The yellow dashed line marks the maximum sheath width. A beam of energetic electrons is indicated by the black dashed arrow.

They are confined by the opposite sheath (hollow cathode effect) [64] causing a higher plasma density within the trench than outside ($s_w < s_p$). At the trench bottom the ion density is low. Therefore, $s_b > s_w$ during the expansion phase. This causes the vertical sheath edge velocity to be higher than the horizontal velocity and, ultimately, electrons are accelerated out of the structure by the expanding sheath from the trench ground ($s_{b2} > s_{b1}$). Very strong excitation above the trench orifice can be observed due to cross-firing of electrons caused by the curved sheath and vertically accelerated electrons from the trench (dashed black arrows). Simulation studies are required to clarify the details of the electron dynamics within the structure.

Figures 5 and 6 depict the vertical excitation dynamics of the rectangular trench and the 90° triangular trench, respectively, in a spatio-temporal excitation plot. Such a plot is generated within a small region of interest (ROI)
Figure 7. Excitation rate in arbitrary units into Ne 2p1 for the upscaled rectangular trench structure at 10 Pa.

of the 2D image data (here: a vertical 4 mm thick stripe horizontally centred inside the structure covering the whole interelectrode distance \( d \)) and presented in a temporal series. These plots cover the whole RF period. An excitation front (indicated by the dashed black arrows) moving upwards with velocities of the order \( 10^6 \text{ m s}^{-1} \) is observed. This is caused by energetic electrons originating from sheath expansion heating. Secondary electron induced excitation can be discarded, since the excitation is maximum during sheath expansion and not at the time of maximum sheath voltage [28]. As mentioned above, due to the strong asymmetry of the discharge no beam is observed at the grounded electrode located at \( z = 70 \text{ mm} \).

Taking the transition between weak sheath and strong bulk excitation as a qualitative criterion for determining the maximum sheath width (yellow dashed line in the figures) we observe that electrons are completely expelled from the rectangular trench structure. The sheath edge is located well above the trench orifice. With respect to the top surface of the structure (black dashed line in the figures) the sheath width is larger above the planar part of the electrode compared to the orifice above the trench orifice [63]. In the case of a triangular trench the maximum sheath edge is located at the orifice of the trench, i.e. significant plasma moulding is observed [65–67].

Inside the rectangular trench with 10 mm width it is not possible to trace the electron beams generated by sheath expansion in front of the vertical trench walls due to the limited temporal resolution of the camera (gate width \( \Delta t = 5 \text{ ns} \)). The propagation of the two opposite electron beams cannot be resolved separately, as the electron beams cross half of the trench width in the time \( \Delta t \). Therefore, the trench geometry is scaled up to gain further insight into the working mechanism of this structure. New trench dimensions are 60 mm (height), 66 mm (width), 80 mm (length). Figure 7 depicts the spatio-temporal evolution of the excitation dynamics of this structure within one RF period at 10 Pa. Strong electron beams with significant horizontal and vertical velocity components are generated in the lower edges of the trench. Strong excitation is observed within most of the RF period (from 15 to 55 ns) due to effective electron heating by the synchronously expanding RF sheaths in front of the trench walls and the ground. In the lower half of the trench this leads to a higher plasma density and a smaller sheath width compared to the trench orifice.

Figure 8(a) depicts the spatio-temporal evolution of the excitation dynamics in the horizontal direction within the trench structure (compare figure 8(b) for the ROI). Due to a higher ratio of the trench width to the electron mean free path, the upscaled trench structure behaves differently from the rectangular trench structure with 10 mm width at fixed pressure. Especially, no reflections of electrons at the opposite sheath can be observed. Instead of observing the dominant excitation at the trench orifice, here it takes place inside the structure.

3.2. Plasma density profiles

Figure 9(a) depicts a typical inhomogeneous radial plasma density profile of a parallel-plate single frequency CCRF plasma in a GEC cell [54, 55] for various gas pressures. In cylindrical geometry the plasma density profile is described by a Bessel function [2]. However, in the GEC cell neither pure cylindrical geometry nor the theoretically expected plasma density profile is realized. The ratio \( R \) of the measured plasma density in the centre of the electrode and at its edge is nearly constant in the pressure range investigated here (\( R \approx 1.6 \), compare figure 9(b)). It represents an inhomogeneity inherent to the parallel-plate configuration.

In the following we demonstrate the effect of structured electrodes on the plasma density profile as a consequence of the modified electron heating. The rectangular trench, 20 mm deep and with a width of 10 mm, is discussed first. The Langmuir probe measurement presented in figure 10 clearly demonstrates the significant effect of the structured electrode on the plasma density at a height of 20 mm.

In transversal direction the density profile above the planar part of the structured electrode resembles that of the parallel-plate case in both magnitude and slope. It is enhanced by a factor of 2 in the vicinity of the structure. Longitudinal measurements above the structure show that
the plasma density is enhanced across the full radius of the electrode compared to the parallel-plate configuration. This is a consequence of the greater interelectrode distance, which is prolonged by the trench depth, and its effect on the excitation dynamics. Necessarily, both curves (transversal and longitudinal) intersect at the centre of the electrode.

The plasma density profile peaks at the centre of the electrode. However, the transversal density profile reaches a slightly higher peak value than the longitudinal measurement. This is a consequence of the Langmuir probe measurement process. In longitudinal direction the probe covers half of the trench when measuring the plasma density at the centre of the electrode. This significantly disturbs the plasma and causes a lower plasma density. In transversal direction the probe measurement at the centre of the electrode disturbs the plasma generation less, which is dominated by the trench structure. Additionally, the profile flank for a positive radial position is steeper compared to that at a negative radial position, i.e. the profile is not perfectly symmetric. Again, this is a consequence of the measurement process. The Langmuir probe takes radial measurements beginning at the negative radial position and by taking subsequent measurement points moving along to the right, i.e. to more positive radial positions. Therefore, measurements on the left (negative radial position) are more reliable than on the right (positive radial position), because in the latter case the probe causes a stronger disturbance of the plasma.

Figure 11 shows a comparison of the transversal density profiles for different structure types with a depth of 20 mm. The measurements are conducted at a height of 20 mm above the trench orifice. At 10 Pa, the steep triangular trench yields the highest peak density followed by the rectangular trench and the 90° triangular trench. The rounded trench shows a significantly lower peak plasma density.

At 15 Pa (compare figure 12) the rectangular trench clearly shows the highest plasma density followed by the steep triangular trench. The 90° triangular trench and the rounded trench show nearly equal plasma densities, which is approximately 25% lower than in case of the other two structures.
Figure 10. Radial plasma density profile both longitudinal and transversal to the rectangular trench at a height of 20 mm at 10 Pa gas pressure. The vertical black dashed lines mark the radius of the electrode.

Figure 11. Radially resolved plasma density profile (transversal direction) for different trench cross sections at 10 Pa obtained at a height of 20 mm. The vertical black dashed lines mark the radius of the electrode.

The behaviour of the plasma density profile at different pressures can be explained as follows. At a high pressure opposite sheaths are formed in all the structures enabling effective confinement via the hollow cathode effect and heating of electrons by bounce (resonance) heating during the phase of sheath expansion. However, in the case of a rounded structure the sheaths show a strong curvature within the trench at 10 and 15 Pa. Confinement worsens as the acceleration of the electrons is predominantly in the vertical direction out of the trench, which also leads to reduced heating via multiple interactions with the expanding sheaths. The 90° triangular trench causes a cross-firing of electrons resulting in convergent fluxes of highly energetic electrons above the trench. This leads to a localized enhancement of the ionization rate and, thereby, of the plasma density. The relative performance of this structure drops with increasing pressure.

Depending on pressure, the rectangular or the 53° triangular trench causes the maximum density. While at 10 Pa the triangular one shows the best performance, at 15 Pa the highest plasma density is achieved by the rectangular trench. This is a consequence of a competitive situation between temporal confinement via the hollow cathode effect and the cross-firing of electrons. At a higher pressure the rectangular trench achieves a better confinement of the electrons compared to the 53° triangular trench as the opposite sheaths are nearly vertical and, hence, achieves a higher plasma density. At lower pressure the sheath does not collapse completely into the rectangular trench. This prevents the electrons from gaining a significant vertical velocity component. Therefore, ionization is enhanced close to the trench and the effect on the plasma density above the structure, which is measured by the Langmuir probe, gets weaker. In this situation, the 53° triangular trench with tilted side walls shows a better performance as electrons are both confined and heated efficiently, and are additionally accelerated out of the trench with a higher vertical velocity component causing an enhancement of the plasma density further in the bulk.

A simple diffusion model for the plasma density profiles is developed in the appendix. The model is based on the physical picture that the plasma is created (a) by the normal background ionization by bulk electrons, plus (b) by localized electron beams propagating vertically to the electrode above the trench.

Qualitatively, this picture is motivated by the observed localized excitation rates measured via PROES.

In the model the finite width of the trench is ignored and the source is represented by a delta function. Further, for the sake of simplicity, the decay of the ionization strength of the beam with increasing distance as well as a spread of the beam by scattering is neglected. The result for a single linear trench oriented in y-direction and located at \( x = 0 \) is:

\[
n(x) = n_p(x) + \frac{S_0 \Lambda}{D_p} \exp(-|x/\Lambda|). \tag{1}
\]
Figure 13. Longitudinal plasma density profile of the rectangular trench structure at 10 Pa and 15 Pa gas pressure, respectively, obtained at a height of 20 mm with and without a dielectric cover on the trench ground.

The enhancement of the density at the origin is given by $A = S_0 \Lambda / \Lambda_1 D_a$ where $S_0$ is the ionization strength of the beam, $\Lambda$ the diffusion length and $D_a$ is the ambipolar diffusion constant. For identical conditions (pressure, height), the relative enhancement is directly proportional to the source strength. The fit made in figure 12 shows very good agreement between the model and the measurement. Also the diffusion length of $\Lambda_1 = 20 \text{ mm}$ is very reasonable. Apparently, the beam from the rectangular trench ($A = 2.9 \times 10^9 \text{ cm}^{-3}$) gives the highest ionization rate. It is almost a factor of two higher than for the round trench structure.

By placing a dielectric cover onto the ground of a trench, the plasma density can be enhanced further. Here, this is done by placing a 2 mm flat glass plate inside the rectangular trench, whose depth is, hence, reduced to 18 mm. Figure 13 shows the results for longitudinal plasma density measurements of the trench with and without the dielectric cover at its ground. PROES measurements do not show enhanced excitation at the phase of maximum RF sheath expansion. Therefore, more secondary electron emission due to the presence of another surface material is not the cause for the increased plasma density. The enhanced plasma density is a consequence of a forced collapse of the RF plasma sheath deep into the structure. The presence of a dielectric requires a local compensation of electron and positive ion fluxes at the glass surface. Thus, a complete sheath collapse is required to allow electrons to reach the dielectric. Consequently, the sheath expands faster and stochastic electron heating is enhanced.

3.3. Plasma uniformity

The insight into the heating dynamics can be utilized to achieve a (radial) homogenization of the plasma density via customized electrode topologies at a given height. Here, ring-structured electrodes are investigated. Figure 14 illustrates the dependence of the radial plasma density profile on the vertical position above the electrode. Langmuir probe measurements at a height of 10 mm and 20 mm, respectively, above a single-ringed electrode (W = 10 mm) at two different vertical heights above the electrode surface and two different pressures. Open symbols denote measurements at 20 mm, full symbols at 10 mm height. Measurements at 20 Pa are marked by $\bullet$ and $\Diamond$, at 10 Pa by $\mathbf{\bullet}$ and $\mathbf{\Diamond}$. Additionally, the modelled density profile is fitted (full lines).

The density profile is much more homogeneous. The diffusion model solution for a ring structure is

$$n(r) = n_p(r) + A \begin{cases} I_0(r/\Lambda), & r < r_t \\ k \cdot K_0(r/\Lambda), & r \geq r_t \end{cases},$$

where $A$ (as in equation (1)) is the ionization strength of the electron beam above the trench located at radius $r_t$ and $I_0, K_0$ are complex Bessel functions.

Exemplarily this formula is fitted to the measurements at a height of $z = 20 \text{ mm}$. Again, $n_p(r)$ is the measured profile of a planar electrode for identical conditions. Also here very good agreement is found with reasonable diffusion lengths of $\Lambda = 22 \text{ mm}$ and $33 \text{ mm}$, respectively. Again, this comparison confirms well the basic picture of localized ionization by beam electrons ejected from the trench.

A double-ringed structure is also investigated. This topology has already been proposed by Ohtsu and Urasaki [24] to control the radial plasma density profile. Here, the outer ring is chosen to be wider than the inner ring (compare figure 2(b)).

In figure 15 the plasma density profile of the double-ringed and the single-ringed structure at a height of 20 mm are compared. As can be seen, very good homogeneity at various gas pressures is achieved across a large part of the electrode radius by utilizing ringed electrode topologies. The lower the gas pressure, the better the homogeneity; i.e. operating the discharge in a non-local regime assists in achieving a homogeneous radial plasma density profile. At higher gas pressures the density profile of the double-ring structure...
It is found that at low pressures these electrons originate from sheath expansion heating. Trench structures lead to an enhanced localized contribution of energetic electrons. Measurements are conducted in pure neon for its favourable spectroscopic properties and pronounced kinetics due to its small cross sections for collisions. We expect comparable results for other gases, e.g. Argon, at lower pressures.

Due to the generation of highly energetic electrons, trench structures cause a local enhancement of the plasma density. Various trench geometries are compared and it is found that the performance of a trench depends on several parameters. In particular, it depends on the combination of gas pressure and shape of the trench side walls, as both determine the form of the resultant RF plasma sheath. Then again, the form of the sheath and the motion of the sheath edge determine the quality of the confinement and both the magnitude and the anisotropy of the acceleration of energetic electrons. These processes can cause a variation of the ionization with height. By placing a dielectric cover onto the ground of a trench, the electron dynamics and the plasma density can be enhanced further.

This fundamental understanding is used to design specific electrode topologies to control the radial plasma density profile. It is demonstrated that ring-trench structured electrodes can enhance both the overall plasma density and lead to a more homogeneous radial plasma density profile at specific heights above the electrode. Multi-ring structures provide a further means for tailoring the homogeneity.

A diffusion model is developed to mathematically describe the effect of trench structures on the plasma density profile. It is demonstrated that the trench structures can be approximated by a delta-function source for the ionization, thus confirming the basic picture of localized ionization by beam electrons ejected from the structure.

Simulation studies are required to validate the mechanisms described in this work.

Appendix. A diffusion model

Trench-like structures of a certain depth lead to a significant (localized) enhancement of the plasma density, which can be utilized to tailor the radial plasma density profile. Here, from the stationary equation for ambipolar diffusion

$$ - \nabla \cdot (D_a \nabla n) = S $$  \hspace{1cm} (A.1)

with a source term $S$ a simple model for the profile of the plasma density $n = n(\vec{r})$ above trench-structured electrodes is derived. $D_a$ is the ambipolar diffusion coefficient.

The source term consists of the normal background ionization by the bulk electrons with an ionization rate $\nu_{iz}$ and a delta-function term presenting the radially localized beam electrons from a trench at position $\vec{r}_i$. Then, the diffusion equation becomes

$$ - D_a \nabla^2 n = \nu_{iz} n + S_0 \delta(\vec{r} - \vec{r}_i). $$  \hspace{1cm} (A.2)

With the ansatz

$$ n = n_p + n_s $$  \hspace{1cm} (A.3)
the plasma density is separated into a contribution $n_p$ of the planar unstructured electrode and a contribution $n_t$ of the trench structure, such that $n_t$ according to

$$-D_n \nabla^2 n_t = \nu_a n_t,$$  \hspace{1cm} (A.4)

is the measured density profile of the planar electrodes setup. The contribution of the trench is calculated via

$$-D_n \nabla^2 n_t = \nu_a n_t + S_0 \delta(\vec{r} - \vec{r}_t) \approx S_0 \delta(\vec{r} - \vec{r}_t).$$  \hspace{1cm} (A.5)

Here, the background ionization is neglected as $\nu_a n_t \ll S_0 \delta(\vec{r} - \vec{r}_t)$, i.e.

$$\int \nu_a n_t \, dV \approx \int S_0 \delta(\vec{r} - \vec{r}_t) \, dV.$$  \hspace{1cm} (A.6)

For an infinitely long linear trench oriented in the $y$-direction and located at $x = 0$ the solution is

$$n(x) = n_p(x) + A \cdot \exp(-|x/\Lambda|),$$

$$A = \frac{S_0 \Lambda}{D_n}.$$  \hspace{1cm} (A.7)

Here, $\Lambda$ is the diffusion length in the $z$-direction. In this simple approximation the finite width of the trench, scattering of the beam electrons, and loss of energy along the $z$-direction is neglected.

With the same approximation, the solution for the circular trench at $r_1$ is:

$$n(r) = n_p(r) + A \cdot \begin{cases} I_0(r/\Lambda), & r < r_1, \\ k \cdot K_0(r/\Lambda), & r \geq r_1 \end{cases}$$  \hspace{1cm} (A.9)

where $I_0$, $K_0$ are complex Bessel functions and $k = I_0/(r_1/\Lambda) / K_0(r_1/\Lambda)$. This model can be extended to more than one trench.

References

[63] www.ep5.rub.de/structuredelectrodes/