Experimental investigations of the magnetic asymmetry effect in capacitively coupled radio frequency plasmas

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Abstract

The electrical asymmetry effect allows control of the discharge symmetry, the DC self-bias, and charged particle energy distribution functions electrically by driving a capacitive radio frequency discharge with multiple consecutive harmonics with fixed, but adjustable relative phases. Recently, Trieschmann \textit{et al} (2013 \textit{J. Phys. D: Appl. Phys.} \textbf{46} 084016) and Yang \textit{et al} (2017 \textit{Plasma Process. Polym.} \textbf{14} 1700087; 2018 \textit{Plasma Sources Sci. Technol.} \textbf{27} 035008) computationally predicted that the discharge symmetry can also be controlled magnetically via the magnetic asymmetry effect (MAE). By particle-in-cell simulations they demonstrated that a magnetic field, that is parallel to the electrodes and inhomogeneous in the direction perpendicular to the electrodes, induces a discharge asymmetry due to different ion densities adjacent to both electrodes. This, in turn, is predicted to lead to the generation of a DC self-bias as a function of the difference of the magnetic field at both electrodes. In this way the MAE should allow control of the mean ion energy at both electrodes as a function of the magnetic field configuration. Here, we present the first experimental investigation of the MAE. In a low pressure discharge operated in argon at 13.56 MHz, we use a magnetron-like magnetic field configuration at the powered electrode, which leads to an inhomogeneous profile of the magnetic field perpendicular to the electrodes. By measuring the DC self-bias and the ion flux-energy distribution function at the grounded electrode as a function of the magnetic field strength at the powered electrode, the driving voltage amplitude and the neutral gas pressure we experimentally verify the concept of the MAE and demonstrate this technology to be a powerful method to control the discharge symmetry and process relevant energy distribution functions.

Keywords: magnetic asymmetry effect, DC self-bias voltage, magnetized plasma, capacitively coupled rf discharge

1. Introduction

10 years ago, Heil \textit{et al} introduced the electrical asymmetry effect (EAE) to control the symmetry of capacitively coupled plasmas (CCPs) electrically based on an analytical model [1, 2]. They used two consecutive harmonics to drive a CCP to control the DC self-bias voltage by varying the relative phase between both harmonics. In a geometrically symmetric reactor, this leads to different mean sheath voltages and ion energies at both electrodes, which can be adjusted by phase control. This was predicted to allow an independent control of the ion flux and the mean ion energy at both electrodes. This prediction was verified later in simulations and experiments including voltage waveforms that contain multiple consecutive harmonics (voltage waveform tailoring (VWT))
[3–14]. The EAE and VWT are important concepts, which allow to control the discharge symmetry, which previously had been determined by the geometric reactor symmetry, i.e. by the ratio of the powered to the grounded electrode surface areas in contact with the plasma. The geometric reactor symmetry, however, cannot be controlled easily.

In 2013, Trieschmann et al [15] studied the effects of a magnetic field, that is parallel to the electrodes and high only adjacent to one electrode, on a dual-frequency CCP by particle in cell simulations (PIC). Similar to a variety of industrially relevant magnetized plasma sources such as radio frequency (RF) magnetrons the magnetic field was assumed to decrease as a function of distance from one electrode to the other, i.e. the plasma was magnetically asymmetric. They showed that such asymmetric magnetic field configurations lead to the presence of different sheaths and ion energy distribution functions (IEDF) at both electrodes in a geometrically symmetric reactor with identical electrode surface areas, \( A_p \) and \( A_g \).

In 2017, Yang et al published PIC simulation results on this magnetic asymmetry effect (MAE) [16]. They showed that (similar to the EAE) the MAE allows to make a geometrically symmetric CCP asymmetric. In their simulations, a static magnetic field was used that is uniform parallel to the electrodes and non-uniform perpendicular to the electrodes. They kept the magnetic flux density at the grounded electrode fixed at 10 mT and increased the magnetic flux density at the powered electrode from 1 to 10 mT, while assuming either a linear or an exponential field profile perpendicular to the electrodes. For a driving frequency of 13.56 MHz and a driving voltage amplitude of 150 V in argon, they found the DC self-bias to increase from −50 V for a magnetic field of 1 mT at the powered electrode to 0 V for a magnetic field of 10 mT at the powered electrode. They observed significant effects of the magnetic field configuration on the potential and electron density profile as well as the ionization rate in the electrode gap, which all became asymmetric in the case of an asymmetric magnetic field configuration. In 2018, the same group published further simulation results on the MAE as a function of the magnetic field gradient, pressure and electrode gap [17]. In these studies magnetic flux densities up to 40 mT were used. They found that the MAE is strongly reduced at high pressures.

These findings can be understood qualitatively based on an analytical model of CCPs originally developed by Czarnecki et al [18]. According to this model the DC self-bias, \( \eta \), in a single frequency low pressure electropositive CCP is given by:

\[
\eta = \frac{1}{1 + \epsilon} \frac{V_0}{\phi_{sp}},
\]

where \( V_0 \) is the amplitude of the driving voltage waveform \( \phi_s(t) = V_0 \cos(\omega t) \), where \( \omega \) is the driving radio frequency, and \( \epsilon \) represents the symmetry parameter:

\[
\epsilon = \left| \frac{\phi_{sg}}{\phi_{sp}} \right| = \left| \frac{I_p}{I_g} \right| \left( \frac{A_p}{A_g} \right)^2 \frac{\bar{n}_g}{\bar{n}_sp}.
\]

Here, \( \phi_{sp} \) and \( \phi_{sg} \) are the maximum sheath voltages at the powered and grounded electrode, respectively. \( I_p \) and \( I_g \) are the respective sheath integrals given in [18]. Their ratio is typically close to unity. \( \bar{n}_g \) and \( \bar{n}_sp \) represent the mean ion densities in the respective sheath.

Based on equation (1), a magnetic field that is parallel to the electrodes and higher at one compared to the other electrode will lead to the generation of a DC self-bias even in geometrically symmetric single frequency CCPs, since the magnetic confinement of electrons is more efficient at the electrode, where the magnetic field is higher. This leads to an enhanced local ionization, since energetic electrons such as ion induced secondary electrons emitted from the electrode are confined by the magnetic field lines. Moreover, due to the reduction of the electron mobility electric field reversal can be induced locally during sheath collapse by the presence of high magnetic fields to ensure flux compensation of electrons and ions at the electrode on time average [19]. This results in a higher mean ion density at one compared to the other electrode, which breaks the symmetry of the discharge (\( \epsilon = 1 \)) and leads to the generation of a DC self-bias. The difference of the magnetic electron confinement at both electrodes can be controlled by adjusting the magnetic field at one electrode, while keeping it constant at the other electrode. This is expected to allow control of the symmetry parameter and the DC self-bias by adjusting the magnetic field configuration. As the DC self-bias corresponds to the difference between the time averaged sheath voltages at both electrodes, the MAE is predicted to allow to control the mean ion energies at both electrodes by adjusting the magnetic field configuration. This is expected to be an important effect, since it allows to tune process relevant plasma parameters in CCPs.

The MAE represents a novel method to control the symmetry and, thus, energy distribution functions of different particle species in CCPs in addition to the geometric reactor symmetry and the EAE. In fact, the MAE is present in a variety of existing magnetized plasma sources, but until now there was no fundamental understanding and no awareness of this effect. Thus, it could not be used in a controlled way. Therefore, its discovery and understanding are expected to have a strong impact in the field of plasma technology. Some prominent examples of such magnetized plasma sources are magnetron discharges [20, 21] and some types of magnetically enhanced reactive ion etchers (MERIEs) [19, 22–38]. In RF magnetron plasmas, permanent magnets are typically located behind the target electrode to generate a static magnetron-like magnetic field inside the plasma that decreases from the target towards the substrate electrode. In regions, where this field is parallel to the target, the cross-field mobility of electrons is reduced and the plasma density as well as the ion flux to the target are enhanced locally. In MERIE reactors, such as those built by commercial companies like Applied Materials Inc. [36–38], typically a magnetic field is generated by coils located outside the vacuum reactor. These coils generate a magnetic field that is directed parallel to the wafer to enhance the plasma density and the ion flux to this electrode. In this scenario, a strong \( E \times B \)-drift of electrons will induce significant lateral non-uniformities of the
plasma across the wafer. To some extent this can be avoided by rotating the external coils around the vacuum chamber or be grading the magnetic field in the plane parallel to the wafer by customizing the current in the magnetic field coils. In order to understand the fundamental physics in such plasma sources, models and simulations of MERIEs were performed based on the assumption that there is no change of the magnetic field in the direction perpendicular to the electrodes [19, 22, 23, 26]. Similarly, fundamental laboratory experiments used Helmholtz coils to generate a magnetic field that is parallel to the electrodes and homogeneous across the electrode gap [28, 29, 32]. Under such conditions the DC self-bias was found to depend on the magnetic field amplitude [28, 29, 38] and electric field reversals during sheath collapse were found to be induced by the presence of such magnetic fields in simulations [19]. In all these fundamental investigations of magnetized CCPs, the MAE is not present, since a uniform magnetic field in the direction perpendicular to the electrodes was used, i.e. the $B$-field is the same adjacent to both electrodes. In practice, however, it is well possible that this is not the case in MERIEs and the MAE is present in such plasma sources, but has been disregarded until now.

So far the MAE has only been predicted and studied computationally. Here, we present the first experimental investigations on the MAE in a geometrically slightly asymmetric CCP with a magnetron-like magnetic field configuration, i.e. a magnetic field that is high at the powered electrode and decreases towards the grounded electrode. This field configuration is markedly different from those typically assumed to be present in MERIE processes. We choose the magnetic field and the driving voltage amplitudes to be similar to those used by Yang et al [16, 17]. However, in our experiment the magnetic field lines are not purely parallel to the electrodes. This is the standard scenario in magnetron plasmas and does not change the basic concept of the MAE. We measure the DC self-bias and the ion distribution function at the grounded electrode as a function of the driving voltage amplitude, magnetic field configuration, and neutral gas pressure in a CCP operated in argon and driven at 13.56 MHz. At low pressures, where the sheaths are collisionless, we compare the measured mean ion energy at the grounded electrode to results of an analytical RF sheath model [18], which allows to understand the MAE in more detail.

The manuscript is structured in the following way: in the next section, the experimental set-up and all diagnostics are introduced. In section 3, the analytical sheath model is described. Our results are presented and discussed in section 4 followed by our conclusions in the final section.

2. Experimental set-up

The experimental set-up is shown schematically in figure 1. It consists of a cylindrical low pressure plasma reactor typically used for sputter deposition and different plasma diagnostics. It is 400 mm high and has a diameter of 318 mm. The powered electrode is located at the top of the chamber. It consists of different layers: the target surface (aluminum), which faces the plasma, a water cooling system behind the target, and permanent magnets located behind the cooling system. A grounded shield surrounds the lateral surface area of the cylindrical electrode. An additional grounded mesh prevents parasitic lateral RF coupling to the reactor walls, which would otherwise result in the generation of a plasma between the electrode shield and the chamber walls. Cylindrical permanent magnets are arranged in two circles inside the powered electrode as shown in figure 2. The outer circle contains 22 sockets for magnets and has a diameter of 90 mm and the inner circle consists of 9 sockets and has a diameter of 36 mm. The sockets are cylindrical and have a diameter and height of 12 mm, respectively. NdFeB permanent magnets with a diameter of 12 mm and a height of 2 or 3 mm are stacked inside these sockets to generate a balanced magnetron magnetic field configuration, which can be adjusted by using a different number/arrangement of these permanent magnets. In this way an azimuthally symmetric balanced magnetron magnetic field configuration is realized, whose amplitude decreases exponentially as a function of distance from the powered target electrode. This is verified by three-dimensional magnetic field measurements in the vented chamber.
using a hall probe (teslameter 3MTS by Senis). In this way the magnetic flux density in all three cartesian coordinates \((B_x, B_y, \text{ and } B_z)\) is measured at different distances from the target for different magnet arrangements. A reference distance from the powered electrode close to the maximum sheath width of 8 mm is chosen and the magnet arrangement is changed systematically to tune the radial \(B\)-field, \(B_r = (B_x^2 + B_y^2)^{1/2}\), at this distance from the powered electrode in a controlled way while maintaining the azimuthal and balanced magnetron field symmetry. In this way radial magnetic fields at this position (parallel to the electrode surface) of 0, 7, 11 (figure 4), 18 and 20 mT are realized (compare table 1). These values are similar to the magnetic fields used in the simulations of Yang et al [16].

The upper target electrode is driven by an RF voltage waveform at 13.56 MHz via an impedance matching. A VI probe (Impedans Octiv Suite) is used to measure the driving voltage amplitude and the current [39].

In order to improve the geometrical symmetry of the reactor, a dielectric confinement is added. It consists of multiple stacked glass disks with an inner hole, whose diameter matches the target diameter of 100 mm. The thickness of each disk is 6 mm. In order to avoid a shortcut between the powered and grounded electrode caused by metallic deposition on the inner side walls of the confinement disks, every second glass disk has a larger inner diameter of 160 mm. The thickness of those disks is only 3 mm to avoid the presence of a plasma between the disks (compare figure 1). By using this dielectric confinement the symmetry parameter of the system is increased from almost zero to \(e \geq 0.3\) for \(B = 0\).

On the grounded electrode a retarding field energy analyzer (RFEA) (Impedans pDC system) is mounted. It is used to measure the IEDF at the grounded electrode [40, 41].

DC self-bias and IEDF measurements are performed in argon gas as a function of the radial magnetic field at a distance of 8 mm from the powered electrode (0–20 mT), while maintaining the azimuthal symmetry of the balanced magnetron magnetic field configuration. Moreover, the neutral gas pressures (1–25 Pa), and the driving voltage amplitude (200–350 V) are varied systematically. The driving voltage amplitude is adjusted by changing the generator power. Figure 3 shows the generator power as a function of the driving voltage amplitude and the magnetic flux density. The driving voltage amplitude rather than the generator power is chosen as control parameter to ensure comparability with previous voltage driven simulations of the MAE [16, 17]. Moreover, the power dissipated to the plasma does not correspond to the generator power, but is difficult to determine accurately and depends on loss channels that are different for each reactor. As the generator only allows to change the power in discrete steps, the driving voltage amplitude can only be changed in discrete steps as well. As the RF current and the phase between current and voltage change as a function of the magnetic field configuration, a given generator power corresponds to different driving voltage amplitudes at different magnetic field configurations. Thus, the voltage amplitude could only be kept constant within about ±3% as a function of the magnetic field configuration. The electrode gap is kept constant at 51 mm.

3. Analytical RF sheath model

The RFEA measurements yield the mean ion energy at the grounded electrode. At low pressures the sheaths are collisionless and the mean ion energy corresponds to the time averaged sheath voltage at this electrode. In order to understand the physical mechanisms behind the formation of the mean ion energy at the grounded electrode as a function of the magnetic field configuration an analytical RF sheath model originally developed by Czarnetzki et al [18] is used. In the frame of this model, a low pressure capacitively coupled discharge is modeled as an equivalent series circuit consisting of a voltage source, a linear blocking capacitor representing the impedance matchbox, and two nonlinear capacitors representing the sheaths. The voltage drop across the plasma bulk is neglected [18].

The goal is to obtain an analytical expression for the time averaged voltage drop across the sheath at the grounded
The sheath voltage at the grounded electrode normalized by the amplitude of the driving voltage waveform, $\bar{\phi}_s f$, can be expressed as a function of time within the RF period as

$$\bar{\phi}_s f(t) = \epsilon (q_t - q(t))^2,$$

(3)

with the symmetry parameter $\epsilon$ introduced in equation (2), the normalized total uncompensated charge in the discharge, $q_t$, and the normalized positive space charge in the sheath at the powered electrode, $q(t)$.

To calculate $\bar{\phi}_s f$ we need to know $\epsilon$, $q_t$, and $q(t)$. The DC self-bias, $\eta$, and the amplitude of the driving voltage, $V_0$, are both measured and, therefore, known, so that the symmetry parameter, $\epsilon$, can be directly calculated by equation (1).

For a single frequency discharge $q_t$ is given by [18]:

$$q_t = \frac{2}{1 + \epsilon}.$$

(4)

Finally, $q(t)$ can be obtained from the following expression [18]:

$$q(t) = -\epsilon q_t + \sqrt{\epsilon q_t^2 - (1 - \epsilon)(\eta + \bar{\phi}_s f(t))}$$

$$\frac{1}{1 - \epsilon},$$

(5)

based on the normalized driving voltage $\bar{\phi}_s f(t) = \cos(2\pi ft)$.

Based on equations (4), (5), and (3) the time averaged voltage drop across the sheath at the grounded electrode can be calculated. If the measured mean ion energy agrees with this time averaged sheath voltage for different magnetic field configurations, the model will provide a detailed understanding of the effect of the MAE on the ion energy, since it allows to relate changes of the ion energy to a change of distinct model parameters, e.g. the symmetry parameter, $\epsilon$.

### 4. Results

An exemplary measurement of the magnetic flux density for a particular magnet configuration ($1 \times 3$ mm magnet in the inner circle per socket, $1 \times 2$ mm magnet and $1 \times 3$ mm magnet in the outer circle per socket, compare table 1) at a distance of 8 mm from the powered electrode is shown in figure 4. The cartesian field components are plotted as a function of $x$ and $y$, i.e. parallel to the electrode surface. Overall, the magnetic field configuration is azimuthally symmetric. This is obvious for the $B_z$ component (perpendicular to the electrode), but also true for the radial component, $B_r = (B_x^2 + B_y^2)^{1/2}$. $B_r$ has a maximum of 11 mT, below the inner ring of magnets and a minimum of $-11$ mT below the
The absolute value of the radial magnetic field component is also 11 mT and located at a radial position in between the two rings of magnets. Similar magnetic field configurations of the same azimuthal symmetry, but with different field magnitudes at a distance of 8 mm from the powered electrode can be realized by using different magnet configurations such as described in Table 1.

Figure 5 shows the measured DC self-bias voltages and calculated symmetry parameters as a function of the amplitude of the driving voltage waveform for different magnetic flux densities measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $\vec{B}$ is maximum. Discharge conditions: argon, 13.56 MHz, 1 Pa, 51 mm electrode gap.

Figure 6 shows the measured DC self-bias and calculated symmetry parameter as well as the mean ion energy at the grounded electrode obtained from RFEA measurements and the analytical RF sheath model at a constant driving voltage amplitude of 300 V $\pm$ 3% as a function of the magnetic flux density measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $\vec{B}$ is maximum. Discharge conditions: argon, 13.56 MHz, 1 Pa, 51 mm electrode gap, 300 V $\pm$ 3%.

Without any magnetic field, the discharge is strongly asymmetric ($\varepsilon \approx 0.3$) due to the geometric asymmetry of the outer ring of magnets, respectively. The absolute value of the radial magnetic field component is also 11 mT and located at a radial position in between the two rings of magnets. Similar magnetic field configurations of the same azimuthal symmetry, but with different field magnitudes at a distance of 8 mm from the powered electrode can be realized by using different magnet configurations such as described in Table 1.

Figure 5 shows the measured DC self-bias voltage, $\eta$, and the symmetry parameter, $\varepsilon$, calculated from the measured DC self-bias and the measured amplitude of the driving voltage waveform, $V_0$, according to equation (1) as a function of $V_0$ for different magnetic fields at 1 Pa. The magnetic field is measured at a distance of 8 mm from the powered electrode at a lateral position, where the radial component of $\vec{B}$ is maximum, in the vented chamber. Figure 6 shows the measured DC-self bias, the symmetry parameter, and the mean ion energy at the grounded electrode obtained from RFEA measurements and from the analytical RF sheath model as a function of the magnetic field at a fixed driving voltage amplitude of 300 V $\pm$ 3% and at a fixed pressure of 1 Pa. Under these conditions the mean ion energy at the grounded electrode can be changed from 45 eV to about 140 eV by changing the magnetic field at a distance of 8 mm from the powered electrode from 0 to 20 mT. This energy range is highly important for material properties such as grain and crystal structure, stress, and density [42].
reactor and the DC self-bias voltage is below $-100$ V for all driving voltage amplitudes. Increasing the magnetic field at the powered electrode leads to an improved confinement and a local reduction of the cross-field mobility of electrons in front of the powered electrode, while the electron confinement and mobility adjacent to the grounded electrode are hardly affected. This leads to an increase of the mean ion density at the powered electrode, $\bar{n}_{sp}$, relative to the mean ion density at the grounded electrode, $\bar{n}_{sg}$, and, according to equation (2), to a corresponding increase of the symmetry parameter as a function of the magnetic field, i.e. the discharge gets more symmetric. Ultimately, this can be caused by a local confinement of energetic electrons such as secondary electrons emitted from the adjacent electrode and phenomena such as magnetically induced electric field reversals during sheath collapse required to ensure a flux compensation of electrons and ions at the adjacent electrode on time average [19]. Our measurements cannot identify such phenomena, but only detect their combined effect on the discharge symmetry. Detailed investigations of these phenomena remain an important topic of future work. Overall, these effects lead to an increase of the DC self-bias (compare equation (1)) and the mean ion energy at the grounded electrode as a function of the magnetic field at constant driving voltage amplitude. Overall, the MAE is based on increasing the mean ion density at one electrode via a high local magnetic field, while the mean ion density at the other electrode, where the magnetic field is low, remains low. In the model, this effect is included by a change of the symmetry parameter as a function of the magnetic field configurations via its sensitivity to the ratio of the mean ion densities at both electrodes. For a fixed magnetic field the absolute value of the DC self-bias increases as a function of $V_0$, since the sheath voltages increase, but the symmetry of the discharge is hardly affected, i.e. the symmetry parameter remains approximately constant. For a magnetic field of 11 mT the symmetry parameter is approximately unity and the DC self-bias is zero, i.e. the geometric discharge asymmetry is compensated by the magnetic asymmetry. For higher magnetic fields at the powered electrode the symmetry parameter is larger than unity and the DC self-bias is positive, i.e. the geometric discharge asymmetry is overcompensated by the magnetic asymmetry.

The measured increase of the mean ion energy at the grounded electrode as a function of the magnetic field is well reproduced by the analytical RF sheath model based on measured values of $\eta$ and $V_0$. The model confirms that this trend is caused by a change of the ratio of the mean ion densities in both sheaths as a function of the magnetic field, since this ratio is the only free parameter in the model.

The model also allows to calculate the mean sheath voltages at both electrodes as a function of the driving voltage amplitude for different magnetic fields (see figure 7). The results show that the absolute values of both sheath voltages increase as a function of the driving voltage amplitude, while increasing the magnetic field leads to a decrease of the absolute value of the mean sheath voltage at the powered electrode, but to an increase of the mean sheath voltage at the grounded electrode. This is explained by the corresponding change of the DC self-bias induced by the MAE.

Higher plasma densities due to an enhanced magnetic confinement of electrons in front of the target lead to higher ion fluxes to the electrodes at high magnetic fields. A similar trend is expected as a function of the driving voltage amplitude. Both trends are verified experimentally here (see figure 8). In fact, the ion flux density measured by the RFEA at the grounded electrode is almost one order of magnitude higher in the 20 mT case compared to the un magnetized scenario. The mean ion energy at the grounded electrode is shown as a function of $V_0$ and the magnetic field in the same figure. It is compared with the mean sheath voltage at the grounded electrode calculated based on the analytical RF sheath model and excellent agreement is found.

Figure 7. Mean sheath voltages at the powered (left) and grounded (right) electrode obtained from the analytical RF sheath model introduced in section 3 as a function of the driving voltage amplitude for different magnetic flux densities measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $B$ is maximum. Discharge conditions: argon, 13.56 MHz, 1 Pa, 51 mm electrode gap.
Figure 9 shows the measured IEDF at the grounded electrode as a function of the magnetic field at a distance of 8 mm from the powered electrode at a fixed driving voltage amplitude of 300 V ± 3%. In addition to a change of the mean ion energy induced by the MAE, also the shape of the IEDF changes as a function of the magnetic field from a single high-energy peak at 0 mT to a bimodal IEDF at 20 mT. This change of IEDF shape as a function of the magnetic field is explained by the increase of the plasma density induced by increasing the magnetic flux density due to the enhanced electron confinement. This leads to an increase of the ion plasma frequency, which, in turn, enables the ions to react faster to the RF potential variation in the boundary sheath. Moreover, this effect can cause the sheath width to decrease as a function of the magnetic field, which reduces the ion transit time through the sheath and allows the ions to react to temporal changes of the sheath voltage more efficiently [43–45].

As shown in figure 10 for a magnetic field of 20 mT, increasing the neutral gas pressure attenuates the MAE. The DC self-bias voltage normalized by the driving voltage amplitude, \( \eta/V_0 \), as well as the symmetry parameter decrease as a function of the pressure and approach 0 and 1, respectively, which corresponds to a symmetric discharge. This is caused by a reduction of the magnetic electron confinement at the powered electrode by collisions due to the collisionally enhanced cross-field transport of electrons. This result shows that the MAE only works efficiently at low pressure. However, such conditions are most frequently used for applications such as RF magnetron sputtering, where the MAE is inherently present and has significant effects on process relevant plasma parameters such as ion energies and fluxes at boundary surfaces. However, this effect has hardly been understood until now and, thus, an advanced process optimization based on scientific understanding of the plasma science was hardly possible.

5. Conclusion

We presented the first experimental investigation of the MAE originally proposed by Trieschmann et al [15] and Yang et al [16, 17] computationally. In a CCP operated at 13.56 MHz in argon at 1 Pa with a balanced magnetron static magnetic field configuration at the powered electrode, we demonstrate that changing the magnetic field close to the powered electrode, while maintaining a magnetic flux density of approximately 0 mT at the grounded electrode, allows to control the discharge symmetry, the DC self-bias, and the mean ion energy at the electrodes. RFEA measurements for different driving conditions show that the measured IEDF at the grounded electrode as a function of the magnetic field at a distance of 8 mm from the powered electrode and at a fixed driving voltage amplitude of 300 V ± 3% at 1 Pa. In addition to a change of the mean ion energy induced by the MAE, also the shape of the IEDF changes as a function of the magnetic field from a single high-energy peak at 0 mT to a bimodal IEDF at 20 mT. This change of IEDF shape as a function of the magnetic field is explained by the increase of the plasma density induced by increasing the magnetic flux density due to the enhanced electron confinement. This leads to an increase of the ion plasma frequency, which, in turn, enables the ions to react faster to the RF potential variation in the boundary sheath. Moreover, this effect can cause the sheath width to decrease as a function of the magnetic field, which reduces the ion transit time through the sheath and allows the ions to react to temporal changes of the sheath voltage more efficiently [43–45].

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Voltage amplitudes show that the mean ion energy at the grounded electrode can be changed by a factor of about 3 by changing the magnetic field at the powered electrode from 0 to 20 mT. Voltage measurements reveal that this is caused by a corresponding change of the DC self-bias. An analytical RF sheath model, that uses the measured DC self-bias and the driving voltage amplitude as input parameters, reproduces the measured trend of the mean ion energy as a function of the magnetic field at the powered electrode and shows that it is caused by an enhancement of the ion density at the powered compared to the grounded electrode induced by the MAE.

More precisely, increasing the magnetic field only at one electrode enhances the magnetic electron confinement locally at this electrode, while it remains unchanged at the other electrode. This leads to the observed spatial asymmetry of the plasma density and is the physical origin of the MAE.

In addition to a change of the mean ion energy at the grounded electrode a change of the shape of the IEDF at the grounded electrode as a function of the magnetic field at the powered electrode is observed. Increasing the magnetic flux density leads to an increase of the plasma density and the ion plasma frequency as well as a potential reduction of the sheath widths. This, in turn allows the ions to react to the RF potential variations inside the sheaths better at high magnetic fields. Therefore, a bimodal IEDF is measured at high magnetic fields, while a single high-energy peak of the IEDF is found at low magnetic fields.

Increasing the neutral gas pressure is found to enhance the collisional transport of electrons across the magnetic field and, therefore, attenuates the MAE.

The MAE is inherently present in a variety of industrial plasma discharges such as RF magnetrons and potentially MERIEs and, thus, it is of high fundamental relevance. If understood, it allows to tune a variety of process relevant plasma parameters and to optimize plasma processes based on scientific understanding. For instance, it allows to control and optimize the IEDFs at different boundary surfaces. One application could be the adjustment of the ion bombardment energy to optimize etch rates, selectivity, and/or the cleaning of walls. MERIE systems could be modified to use the MAE by moving the external Helmholtz magnetic field coils off center in the direction perpendicular to the electrodes. In this way, the field would no longer be uniform in this direction and the MAE could be used. The difference in magnetic field magnitude at both electrodes would be determined by the vertical position of the coils.

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