The magnetic asymmetry effect in geometrically asymmetric capacitively coupled radio frequency discharges operated in Ar/O₂

M Oberberg¹,6, B Berger¹, M Buschheuer¹, D Engel², C Wölfel³, D Eremin², J Lunze⁵, R P Brinkmann², P Awakowicz¹ and J Schulze¹,4,5

¹ Institute of Electrical Engineering and Plasma Technology, Ruhr University Bochum, Universitaetsstrasse 150, 44801 Bochum, Germany
² Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Universitaetsstrasse 150, 44801 Bochum, Germany
³ Institute of Automation and Computer Control, Ruhr University Bochum, Universitaetsstrasse 150, 44801 Bochum, Germany
⁴ Key Laboratory of Materials Modification by Laser, Ion, and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, People’s Republic of China
⁵ Department of Physics, West Virginia University, Morgantown, WV 26506, United States of America

E-mail: oberberg@aept.rub.de

Received 12 February 2020, revised 22 April 2020
Accepted for publication 10 June 2020
Published 28 July 2020

Abstract

Previous studies in low pressure magnetized capacitively coupled radio frequency (RF) plasmas operated in argon with optimized geometric reactor symmetry have shown that the magnetic asymmetry effect (MAE) allows to control the particle flux energy distributions at the electrodes, the plasma symmetry, and the DC self-bias voltage by tuning the magnetron-like magnetic field adjacent to one electrode (Oberberg et al 2019 Plasma Sources Sci. Technol. 28 115021; Oberberg et al 2018 Plasma Sources Sci. Technol. 27 105018). In this way non-linear electron resonance heating (NERH) induced via the self-excitation of the plasma series resonance (PSR) was also found to be controllable. Such plasma sources are frequently used for reactive RF magnetron sputtering, but the discharge conditions used for such applications are significantly different compared to those studied previously. A high DC self-bias voltage (generated via a geometric reactor asymmetry) is required to realize a sufficiently high ion bombardment energy at the target electrode and a reactive gas must be added to deposit ceramic compound layers. Thus in this work, the MAE is investigated experimentally in a geometrically asymmetric capacitively coupled RF discharge driven at 13.56 MHz and operated in mixtures of argon and oxygen. The DC self-bias, the symmetry parameter, the time resolved RF current, the plasma density, and the mean ion energy at the grounded electrode are measured as a function of the driving voltage amplitude and the magnetic field at the powered electrode. Results obtained in pure argon discharges are compared to measurements performed in argon with reactive gas admixture. The results reveal a dominance of the geometrical over the magnetic asymmetry. The DC self-bias voltage as well as the symmetry parameter are found to be only weakly influenced by a change of the magnetic field compared to previous

© 2020 The Author(s). Published by IOP Publishing Ltd Printed in the UK
The deposition of thin films is a key procedure for many applications in modern industry [15, 40]. A wide range of different technological fields relies on it: for instance, high quality thin films are needed for optical components, microelectronics and medical applications [29, 41, 56, 66]. An important and commonly used thin film deposition process is physical vapor deposition (PVD) [53]. A solid target is put in contact with a plasma at low pressure. Highly energetic ions, e.g. argon ions, bombard this target and are able to break the surface bonds to sputter atoms from the solid. These particles can then condense on other surfaces in contact with the plasma, for example on a substrate. Commonly used processes are (pulsed) DC or mid-frequency magnetron plasmas or high power pulsed magnetron sputtering (HPPMS) [7, 8, 31, 35]. HPPMS is a fairly new technique that provides lower sputter rates in comparison to classical magnetron sputtering, a high degree of ionization of sputtered atoms, self-sputtering, and gas rarefaction. It is characterized by a strongly non-linear dependence of the sputter yield on the target voltage [7, 10, 19, 42, 55]. Magnetron plasma suffer from a poor degree of target material utilization, since the sputtering mainly takes place underneath the magnetized torus region adjacent to the target, i.e. within the racetrack. The use of additional reactive gas admixtures provides the opportunity to deposit ceramic compound layers using a metallic target surface. For instance, oxygen in the gas phase reacts with sputtered aluminum and forms aluminum oxide films at the substrate surface. The production of high-quality thin coatings requires a precise control of reactive sputter processes [79–81]. The reactive gas also interacts with the target and the formation of ceramic surface layers on the target can lead to arcening, especially in DC magnetrons. Moreover, non-linear hysteresis effects are known to affect surface characteristics and to lead to instabilities [3, 4, 7, 31, 50, 67]. Pulsing suppresses arcing and still shows high deposition rates [2, 6, 8, 31]. Using higher frequencies, e.g. a radio frequency (RF) of 13.56 MHz, also avoids arcing effects [9, 43, 71]. Higher frequencies induce higher electron densities in the plasma bulk and, thus, a higher ion flux towards the target [1, 34, 46, 49, 75, 82]. At low pressures, where the mean free path of the ions becomes larger than the sheath thickness, the DC self-bias voltage is an indicator for the ion bombardment energy at the target surface. A summary of the different applications and the physics of sputter deposition can be found in the review of Greene [26].

In order to facilitate the control of such capacitively coupled RF (CCRF) plasmas a detailed understanding of the electron power absorption dynamics in such magnetized discharges is needed, since it strongly affects process relevant parameters such as the different species densities, fluxes, and energy distribution functions. The magnetic asymmetry effect (MAE) [47, 48] provides the opportunity to control process relevant plasma parameters such as the DC self-bias voltage by adjusting the magnetic field at the target. This way to magnetically control the plasma symmetry is conceptionally similar to the concept of the electrical asymmetry effect (EAE), which allows to control the DC self-bias by tailoring the driving voltage waveform [17, 18, 28, 63–65]. Both, the MAE and the EAE, allow to control the plasma symmetry.

Recent studies investigated different heating modes in unmagnetized CCRF plasmas: the acceleration of electrons by the expanding sheath (α-mode), the ionization due to secondary electrons (γ-mode) [25, 30, 36, 52, 59, 60, 73], the electron heating due to the plasma series resonance (PSR), and the related non-linear electron resonance heating (NERH) mechanisms [5, 12, 44, 45, 54, 61, 62]. Wilczek et al and Schulze et al studied the spatio-temporally resolved electron dynamics theoretically in these plasmas including the electron power absorption by an analysis of the moments of the Boltzmann equation. The current continuity in the presence of electron beams and electric field reversals generated by the expanding sheath and the interaction with bulk electrons are described in detail in [59, 76–78].

For a general understanding of these discharges, Czarnetzki et al introduced an analytical model that describes the DC self-bias voltage $\eta$ in a low pressure electropositive CCRF plasma [13]. Using a single frequency sinusoidal voltage waveform with an amplitude $V_0$ and neglecting the voltage drop across the plasma bulk, the DC self-bias voltage is given by:

$$\eta = -V_0 \frac{1 - \epsilon}{1 + \epsilon},$$  \hfill (1)

where $\epsilon$ is the symmetry parameter and corresponds to the absolute value of the ratio of the maximum voltage drops across the grounded ($\hat{\phi}_g$) and the powered ($\hat{\phi}_p$) sheath:

$$\epsilon = \frac{\hat{\phi}_g}{\hat{\phi}_p} = \left(\frac{A_p}{A_g}\right)^2 \frac{I_{sp}}{I_{sg}} \frac{n_{sp}}{n_{sg}}.$$  \hfill (2)

Here, $A_p$ and $A_g$ are the surface areas of the powered and grounded electrode, respectively. $n_{sp}$ and $n_{sg}$ represent the
mean ion densities in the powered and grounded sheath. $I_{eg}$ and $I_{ep}$ are the sheath integrals of the respective sheath. To a good approximation, the ratio of these integrals is typically unity [13].

For the purpose of sputtering, usually a static magnetic field is applied close to the target electrode. This locally enhances the ion density in the adjacent sheath at one of the electrodes. According to equation (2), this also affects the symmetry parameter and the DC self-bias voltage based on equation (1).

In previous studies, this effect was introduced as the MAE [47, 48]. It can be used to control the DC self-bias voltage, the discharge symmetry, the particle flux energy distribution functions and the heating dynamics in a CCRF plasma by changing the magnetic flux density at one of the electrodes only. In recent works, the MAE was studied computationally [72, 83, 84] and a strong influence of the magnetic field on the discharge properties by applying a magnetic field parallel to the electrode surfaces, that decreases as a function of distance from this electrode, was revealed. Experimental studies [48] validated these results using a magnetron-like magnetic field configuration in an argon discharge with optimized geometric symmetry. In this reactor, the symmetry parameter could be controlled by adjusting the magnetic field. This was found to strongly affect the mean ion energies at both electrodes. Further results showed the opportunity to control the RF current, i.e. the self-excitation of the PSR, as well as the NERH by adjusting the magnetic field at the powered electrode [47].

Studying the electron heating dynamics in magnetized capacitively coupled plasmas is a hot topic of current research in low temperature plasma science. Turner et al came to the conclusion that even weak magnetic fields (e.g. 1 mT) perpendicular to the electric field lines change the heating mode of a low pressure argon RF plasma. Unmagnetized discharges under these conditions are driven by electron acceleration by the expanding sheath with presheath fields that generate electron ‘pressure heating’. In contrast to this, in magnetized CCRF plasmas electrons are heated predominantly by ohmic heating due to a magnetically enhanced plasma resistance [74]. Investigations of the electron power absorption requires numerical modeling, which is not possible in one-dimensional simulations due to the inherently two-dimensional structure of the magnetic field. An example can be found in Gerst et al [24], who described the behaviour of stripe structures formed by electrons due to their interaction with the magnetic field and chamber walls. Two-dimensional magnetic fields and particle drifts invalidate one-dimensional simulations and plasma description.

In this work, we investigate the MAE experimentally in a geometrically asymmetric CCRF discharge operated in mixtures of argon and oxygen based on measurements of the DC self-bias voltage, the symmetry parameter, the ion energy, the electron density, and the RF current as a function of the driving voltage amplitude and the magnetic field at the powered electrode. In this way and in contrast to previous work, which investigated symmetric argon discharges [47, 48], we investigate a scenario that is relevant for reactive sputtering in industry. We investigate the effects of a geometric reactor asymmetry as well as of the introduction of oxygen as a reactive gas on the MAE. The set-up includes a variable magnetron-like magnetic field configuration, inducing a magnetic asymmetry and closed field lines at the powered electrode. This is different from most other investigations with a magnetic field parallel to the electrodes.

The manuscript is structured as follows: the experimental set-up is described in section 2 including the applied diagnostics. Then, the results are presented in pure argon (section 3.1) and argon/oxygen mixtures (section 3.2) in this geometrically asymmetric discharge. The conclusions in section 4 summarize the results.

2. Experimental set-up

The experimental set-up used in this work is a modification of the set-up used in references [47, 48]. It is shown schematically in figure 1 and consists of a cylindrical vacuum chamber with a height of 400 mm and a diameter of 318 mm. The reactor walls are grounded. The powered electrode is mounted at the top of the chamber and is surrounded by a grounded shield as well as a grounded mesh to prevent parasitic RF coupling to the reactor walls. The powered electrode has a diameter of 100 mm and includes NdFeB permanent magnets, which are arranged in two concentric rings to create an azimuthally symmetric balanced, magnetron-like magnetic field configuration. The magnets are located behind the electrode surface and are not in contact with the plasma. As a reference, the maximum radial component of the magnetic flux density is measured at an axial distance of 8 mm from the powered electrode surface in the absence of a plasma by a Hall probe. By stacking different permanent magnets, magnetic flux densities of 0 mT, 7 mT, 11 mT, 18 mT, and 20 mT can be reached at this reference point. A more detailed description of the configuration and measurements of the magnetic flux density can be found in reference [48].

The set-up is used for RF magnetron sputtering, which requires a high mean sheath voltage at the powered target electrode. This accelerates ions towards the aluminum surface and leads to sputtering of metal atoms. Just like the powered electrode, the grounded electrode is made of aluminum. The gap distance between both electrode surfaces is 52 mm.

The powered electrode is driven by a sinusoidal RF voltage waveform at 13.56 MHz with an amplitude ranging between $\phi_0 = 150 \text{ V}$ and $\phi_0 = 400 \text{ V}$. A VI-probe (Impedans Octiv Suite) is used to measure the driving voltage amplitude and the current. Additionally, the DC self-bias voltage is measured.

In the grounded electrode, a self-excited electron resonance spectroscopy (SEERS) sensor is implemented, which measures the RF current as a function of time at the center with nanosecond time resolution within the RF period. According to Klick and Franz [21, 33] the measured time resolved current can be used to analyze the electron power absorption. The SEERS sensor measures the current in the center of the grounded electrode only (with a diameter of 1 cm).
The magnetic field decreases strongly as a function of the distance to the powered electrode. Thus, at the grounded electrode no magnetic field is present that can influence the SEERS diagnostic.

Below the radial edge of the powered electrode, a multipole resonance probe (MRP) is placed to measure the plasma density. It is located at the axial center of the electrode gap with a radial distance of 50 mm from the symmetry axis. At this position, the magnetic field is negligible and does not influence the measurement. For the measurement, a vector network analyzer generates a frequency sweep signal, which is coupled via the probe into the plasma. The system's response shows a resonance close to the electron plasma frequency, i.e. the reflected signal intensity is minimum at this resonance frequency, since power is absorbed efficiently by the plasma. According to Lapke, from this resonance frequency, the electron density can be calculated as described in references [37–39]. Further information about the concept of the MRP can be found in references [20, 57, 58, 69, 70].

In order to measure the ion flux energy distribution function at the substrate surface a retarding field energy analyzer (RFEA) (impedans semion system) is mounted on the grounded electrode [22, 23].

All measurements are performed in pure argon (25 sccm) or in an argon/oxygen mixture (25 sccm + 3 sccm) as a function of the radial magnetic field strength at the reference position and as a function of the driving voltage amplitude. The oxygen mass flow is chosen to be high enough to completely poison the aluminum target surface. This status of the target surface was ensured based on the following approach applied at fixed generator power: for all RF powers that yield the driving voltage amplitude. The oxygen flow was increased and the DC self-bias voltage was monitored. According to Depla et al [16] the absolute value of the DC self-bias decreases as a function of the fraction of the target that is oxidized, since the secondary electron emission coefficient and, thus, the discharge current increases. Thus, at constant power, the DC self-bias voltage decreases. Once the target is fully oxidized increasing the O₂ admixture does not cause any change of the DC self-bias anymore. Here, in all cases this status was reached at oxygen flows of less than 3 sccm, i.e. for an O₂ flow of 3 sccm the target is fully poisoned under all conditions used in this work. In this way the effects of a change of the target surface material induced by the presence of a reactive gas on the plasma characteristics are studied. A neutral gas pressure of 1 Pa is used for all measurements. In order to set the driving voltage amplitude, the generator power is varied.

3. Results

3.1. Geometrically asymmetric RF magnetron operated in pure argon

Firstly, we investigate the effect of the geometrical reactor asymmetry on the MAE in a pure argon discharge. According to reference [48], where a glass confinement was used to optimize the geometric discharge symmetry, and figures 2(a) and (b), it is possible to control the reactor asymmetry and even reverse it by adjusting the magnetic field in a CCP with optimized geometric reactor symmetry. This is illustrated by the fact that the symmetry parameter, ε, can be changed from less than unity to values above unity by increasing the magnetic field measured at the reference position adjacent to the powered electrode. This means that the voltage drop across the grounded electrode sheath will be higher than the voltage drop across the sheath at the driven electrode and the DC self-bias voltage will get positive, if the symmetry parameter rises above 1. The results obtained for the geometrically asymmetric set-up strongly differ from those obtained in the more symmetric scenario. For the geometrically asymmetric reactor, the measured DC self-bias voltage and the symmetry parameter are shown in figures 2(c) and (d) as a function of the applied voltage amplitude and the magnetic flux density. Due to the higher geometric asymmetry the DC self-bias voltage is negative for all magnetic fields and voltage amplitudes studied here. It decreases linearly as a function of the applied voltage amplitude. Increasing the magnetic flux density from 0 mT to 20 mT leads to a more positive DC self-bias voltage, e.g. at \( V_0 = 300 \) V, \( \eta \) will increase from \(-250 \) V to \(-200 \) V, if the magnetic field is changed from 0 mT to 20 mT. In comparison to the results obtained in the more geometrically symmetric reactor under otherwise identical conditions, this small change of 50 V (vs 200 V in the more symmetric reactor) shows that the effect of the geometrical asymmetry on the DC self-bias prevails over the effect of the MAE on the DC self-bias. This is also illustrated by the symmetry parameters calculated based on equation (1) as illustrated in figures 2(b) and (d). For instance at a driving voltage amplitude of 300 V, increasing the magnetic field from 0 mT to 20 mT results in an increase of the symmetry parameter from about 0.3 to about 1.45 in the more symmetric reactor, while it remains far below unity in the geometrically asymmetric scenario. In contrast to the measurements performed in the more symmetric
Figure 2. DC self-bias voltage measured in a RF magnetron with optimized geometric reactor symmetry ((a), results from reference [48]) and in a strongly asymmetric RF magnetron (c) as well as the calculated symmetry parameter obtained in a RF magnetron with optimized geometric reactor symmetry ((b), results from reference [48]) and in a strongly asymmetric RF magnetron (d) 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 $\vec{B}$ is maximum. Discharge conditions: argon, 13.56 MHz, 1 Pa.

Figure 3. Ion flux-energy distribution functions measured by a RFEA 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, 300 V, 13.56 MHz, 1 Pa.

reactor [47, 48], the symmetry parameter decreases as a function of the applied voltage amplitude in the asymmetric case. By increasing the voltage amplitude, the plasma expands more and more towards the grounded chamber walls. According to equation (2), this will enhance the discharge asymmetry, since the ion density in vicinity of the grounded chamber walls will be enhanced. In the more symmetric reactor used for the previous studies, the plasma was shielded from the grounded chamber walls by a glass confinement and, thus, the plasma was not able to expand towards these walls. Generally, the dependence of the DC self-bias on the driving voltage amplitude, $V_0$, is more pronounced compared to the dependence of the symmetry parameter on the voltage, since, based on equation (1) and for a given reactor symmetry (a constant value of $\epsilon$), the DC self-bias is proportional to the driving voltage, i.e. its absolute value increases as a function of $V_0$. The symmetry parameter, however, corresponds to the ratio of the maximum sheath voltages at both electrodes, which both increase as a function of $V_0$, but their ratio and, thus, $\epsilon$ is much less sensitive to the driving voltage amplitude.

Figure 3 shows ion flux-energy distribution functions measured at the grounded electrode of the geometrically asymmetric reactor by a RFEA in pure argon at 1 Pa and $V_0 = 300$ V for different magnetic flux densities measured at the reference position. Due to the low neutral gas pressure and the small sheath width, the sheath at the grounded electrode is almost collisionless and, thus, a single high energy peak is observed. In agreement with the results shown in figures 2(c) and (d), the shape of the measured distribution functions does not change.
Figure 4. Mean ion energies measured at the grounded electrode of the geometrically asymmetric RF magnetron (a) and electron densities measured at an axial position in the middle of the electrode gap and at a radial position corresponding to the edge of the powered electrode in the geometrically asymmetric RF magnetron (b) 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 \( \mathbf{B} \) is maximum.

Discharge conditions: argon, 13.56 MHz, 1 Pa.

much as a function of the magnetic field, because the reactor symmetry and the DC self-bias are mostly determined by the geometric asymmetry and only weakly by the magnetic asymmetry. This is strongly different compared to previous measurements in a reactor characterized by an optimized geometric symmetric, where the magnetic asymmetry (controlled by the magnetic field at the powered electrode) had a strong effect on the discharge symmetry, the DC self-bias, and the shape of the IEDF at the grounded electrode [48]. Figure 3 also shows an increase of the ion flux to the grounded electrode as a consequence of the enhanced magnetic electron confinement and ionization at the powered electrode.

The mean ion energies calculated from the IEDFs measured at the grounded electrode as a function of the driving voltage amplitude and the magnetic field (measured at the reference position) in the geometrically asymmetric RF magnetron are shown in figure 4(a). The range in which the mean ion energies can be adjusted by tuning the magnetic field, i.e. via the MAE, is limited to less than 10 eV due to the strong geometric reactor asymmetry, which prevails over the magnetic asymmetry. The low sheath voltages at the grounded electrode do not allow to significantly adjust the ion energies at the substrate. Without the magnetic field, the mean ion energies increase linearly with the driving voltage amplitude. Applying the highest magnetic field of 20 mT, a maximum of the mean ion energy occurs at a voltage amplitude of approximately 225 V, before it decreases again at higher voltages. This might be a consequence of the increased voltage drop across the bulk as a function of the applied magnetic field. Thus, under those conditions the accuracy of the model and, thus, of the calculation of the symmetry parameter is limited at high magnetic fields and driving voltage amplitudes due to the negligence of the voltage drop across the bulk. At higher voltage amplitudes and higher magnetic fields this effect gets stronger. Furthermore, a stronger magnetic field shifts the maximum of the ion energy to lower voltage amplitudes. Thus, the decrease of the mean ion energy as a function of the driving voltage amplitude starts at lower values of \( V_0 \). Hence, the mean ion energy for the highest magnetic flux density of 20 mT is lower compared to the mean ion energy for 18 mT when applying a voltage amplitude higher than 150 V.

Results of measurements of the electron density performed by the MRP at an axial position in the middle of the electrode gap and at a radial position located underneath the edge of the powered electrode are shown in figure 4(b). The electron density increases by a factor of 6–10 as a function of the magnetic field at all applied voltages. The dependence on the voltage amplitude is almost linear with and without an applied magnetic field. As the probe position is fixed, the increase of the electron density as a function of the magnetic flux density is a consequence of the enhanced ionization in the magnetized zone due to a better magnetic electron confinement.

For a constant voltage amplitude of 300 V, the current density measured at the center of the grounded electrode of the geometrically strongly asymmetric reactor using a SEERS sensor is shown as a function of time within two RF periods in figure 5. The measured current is normalized by its maximum. Due to the enhancement of the plasma density as a function of the magnetic field, this maximum increases as a function of the magnetic flux density. The expansion phase of the sheath adjacent to the powered electrode starts at 0 ns. The unmagnetized case (see figure 5(a)) shows strong high frequency oscillations of the current, which are damped within one RF period. As described in previous studies of unmagnetized CCRF plasmas, these high frequency oscillations are caused by the self-excitation of the plasma series resonance (PSR) [76]. Electrons are accelerated by the expanding sheath at the powered electrode and form a highly energetic electron beam. When electrons move away from the powered electrode, the measured current density is negative. A positive current corresponds to electrons that move towards the powered electrode. When the first electron beam is formed and propagates away from the expanding sheath edge at the powered electrode, the inert positive ions are left behind and a positive space charge region is formed on the bulk-side of the expanding sheath edge [76].
In this way an electric field is generated that accelerates bulk electrons back towards the powered electrode and, hence, the current direction changes and gets positive after some time. When those electrons hit the expanding sheath edge, they are accelerated towards the plasma bulk by the expanding sheath and these dynamics start again. These high frequency PSR oscillations dominate the RF current waveform. In figure 6(a) the normalized fast Fourier transformation (FFT) of the measured current is shown for 0 mT and the maximum is found at 203.4 MHz, which is identified as the PSR frequency.

Applying a magnetron-like magnetic field generates a magnetic discharge asymmetry via the MAE. The plasma density increases significantly in front of the powered electrode. Moreover, in regions, where the magnetic field is parallel to the electrodes and perpendicular to the axial electric field, the mobility of electrons perpendicular to the magnetic field lines and the electrode surfaces is greatly reduced. This results in an enhanced resistance of the plasma at high magnetic fields and, according to Turner et al [74], can induce a transition of the dominant electron power absorption mechanism from pressure to ohmic heating including the generation of reversed electric fields during sheath collapse at the powered electrode during the phase of the local sheath collapse. Overall, increasing the magnetic field strongly affects the shape of the current waveform measured at the grounded electrode as shown in figures 5(b)–(e). The Fourier spectrum shown in figure 6 reveals the attenuation of higher harmonics as a function of the magnetic field. Thus, fewer oscillations occur within each RF period. At low magnetic fields the first minimum of the current corresponds to the global minimum of the waveform similar to the unmagnetized case. However, increasing the magnetic field causes the second minimum to become stronger compared to the first minimum. Overall, the observed effects of the magnetic field on the current waveform and the self-excitation of the PSR are significant, but are clearly not fully understood. Here, we present these experimental findings as a basis for the development and experimental verification of future models that might be able to provide a complete explanation. Qualitatively we expect the following effects to play an important role: when the sheath at the powered electrode is collapsed at 0 ns and starts its expansion phase, electrons are accelerated towards the plasma bulk and the PSR is self-excited. The presence of magnetic field lines parallel to the electrode surface is expected to reduce the electron crossfield transport, so that bulk electrons cannot flow back towards the expanding sheath edge easily. Thus, the positive space charge left behind at the expanding sheath edge shortly after the formation of the first group of energetic electrons due to sheath expansion heating might prevail longer. Thus, the second minimum of the current might occur later and might get stronger as a function of the magnetic field strength, since the electric field required to accelerate bulk electrons back towards the expanding sheath edge might increase due to the enhanced plasma resistance. A more detailed investigation of the spatio-temporal electron power absorption dynamics in RF magnetron plasmas is
required to clarify these mechanisms. This is, however, not the scope of this work.

Figure 7 shows the normalized accumulated electron power absorption as a function of time within the RF period calculated according to Ziegler et al [85] as:

\[ P_e(t) = \frac{1}{T_{RF}} \int_{0}^{t} P_R \sqrt{\gamma(t)} \, dt \sim \int_{0}^{t} \sqrt{\gamma(t)} \, dt. \quad (3) \]

Here, \( T_{RF} \) is the duration of one RF period, \( P_R \) is the plasma resistance, and \( j \) is the RF current density. In the unmagnetized case, there is a strong increase of the dissipated power at the beginning of the RF period due to sheath expansion heating of electrons at the powered electrode [85]. Due to the geometric discharge asymmetry the sheath adjacent to the grounded electrode is small and, thus, there is essentially no electron power absorption during the second half of the RF period, when the sheath expands at the grounded electrode. Increasing the magnetic field affects the time resolved accumulated power dissipated to electrons significantly. The changes of the shape of the RF current waveform as a consequence of the modified self-excitation of the PSR as a function of the magnetic field lead to multiple plateaus of the accumulated power dissipated to electrons during the first half of the RF period, when the sheath expands at the powered electrode. According to figure 2(d) increasing the magnetic field enhances the reactor symmetry. Thus, sheath expansion heating of electrons at the grounded electrode during the second half of the RF period is enhanced by increasing the magnetic field. Moreover due to the magnetically enhanced plasma resistance, electric field reversal during the sheath collapse at the powered electrode, where the magnetic field is high and the electron cross-field transport is reduced, are known to be generated during the second half of the RF period [74]. Thus, electron power absorption is also enhanced at the powered electrode during the second half of the RF period as a function of the magnetic field strength. Consequently, figure 7 shows an increase of the accumulated power dissipated to electrons during the second half of the RF period as a function of the magnetic field at the powered electrode.

3.2. Geometrically asymmetric RF magnetron operated in Ar/O2

In this section, measurements of the DC self-bias, the mean ion energy at the grounded electrode, the plasma density (measured 8 mm below the powered electrode at its radial edge), and the RF current waveform as a function of the magnetic field (measured at the reference position) are presented for mixtures of argon with oxygen [25 sccm argon + 3 sccm O2] in a geometrically strongly asymmetric reactor. These results are compared to measurements done in pure argon under otherwise identical discharge conditions (13.56 MHz, 1 Pa, 300 V driving voltage amplitude) to identify the effects of O2 on the measured parameters. Oxygen is an electronegative and molecular gas. Its presence changes the volume chemistry as well as the electron dynamics. In the magnetized zone close to the powered electrode, the dissociation of molecular oxygen is expected to be larger than in the unmagnetized zone, similar to the situation in inductively coupled plasmas [11, 27, 32, 68].

Depending on the O2 admixture and the discharge conditions target poisoning can occur, i.e. the aluminum target surface is oxidized and Al2O3 is formed at the plasma facing target surface. Under the conditions studied here, the target is fully poisoned. Such conditions are chosen on purpose in order to maximize the effects of the O2 admixture on the discharge and, thus, to facilitate identifying them. Depending on the driving voltage amplitude, target poisoning is known to have drastic effects on RF magnetron sputtering applications by modifying the sputter rate as well as the secondary electron emission coefficient.

In figure 8 the measured DC self-bias voltage (a) and the calculated symmetry parameter (b) are shown as a function of the magnetic flux density for a driving voltage amplitude of 300 V. The black squares and red dots show results obtained in pure argon and in argon with an admixture of oxygen (25 sccm argon + 3 sccm O2), respectively. For the unmagnetized case, the DC self-bias voltages are almost the same, although the target is completely covered by aluminum oxide in the Ar/O2 gas mixture. Adding a magnetic field of 20 mT to the Ar/O2 discharge leads to an increase of the DC self-bias voltage from −250 V to −180 V. For all magnetic flux densities, the measured DC self-bias is significantly higher in Ar/O2 compared to the pure argon case. A similar behaviour is observed for the symmetry parameters. In the unmagnetized scenario, it is approximately the same in pure argon and in the Ar/O2 mixture. The discharge gets more symmetric as a function of the magnetic flux density for both gas mixtures. Again the values for the Ar/O2 mixture are higher than those for pure argon. This is expected to be caused by the presence of a higher secondary electron emission coefficient for the oxidized aluminum surface [14, 51]. According to Phelps and Petrovic [51], the difference between heavy particle induced secondary electron emission coefficients of clean and oxidized metal surfaces depends on the incident heavy particle energy. At high bombardment energies above about 150 eV, the secondary electron emission coefficient is higher for oxidized surfaces. Below this threshold, this emission coefficient is higher for clean metal surfaces. For discharge conditions used for sputtering, such as the higher voltage amplitudes studied here, the ion bombardment energy at the target is above this threshold and, thus, oxidized metal surfaces have higher emission coefficients. In the presence of a magnetic field adjacent to the powered target electrode secondary electrons are confined to the magnetized region adjacent to the target and enhance the plasma density close to the target by ionization. This causes the symmetry parameter and the DC self-bias to be higher in Ar/O2 compared to pure Ar in the presence of a magnetic field. In the unmagnetized case and at the low pressure of 1 Pa, secondary electrons are not confined to the target region and do not enhance the plasma density via ionization at the powered electrode. Thus, there is no effect of adding O2 on the symmetry parameter and the DC self-bias in the unmagnetized scenario. In addition to this, the presence of a magnetic field at the target can induce electric field reversals during sheath collapse. This would also enhance the ionization adjacent to the target and would have
similar effects on the symmetry parameter and the DC self-bias. Clearly, these are only hypotheses to explain the experimentally observed trends. Simulation and/or model work is required to ultimately clarify these issues in future work.

The RFEA measurements of the ion flux energy distribution functions at the grounded electrode as a function of the magnetic field for the Ar/O₂ mixture show qualitatively similar results compared to those shown in figure 3 for pure argon, i.e. a single high energy peak, which indicates the presence of a collisionless sheath, is observed. Thus similar to pure argon, the geometric reactor asymmetry dominates also in Ar/O₂ and does not allow to control the IEDF efficiently by tuning the magnetic field. The mean ion energy at the grounded electrode is shown in figure 9(a) as a function of the magnetic field for both gas mixtures. It shows a complex trend characterized by an initial increase up to a maximum, which is then followed by a decrease of the mean ion energy. This maximum is reached at a low magnetic field of 7 mT in Ar/O₂, while it is reached at a higher magnetic field of 18 mT in pure argon. For the measurements of the mean ion energy at the grounded electrode in Ar/O₂, a second peak occurs at 18 mT. However, the difference to the values measured with a magnetic flux density of 11 mT and 20 mT lies in the range of the accuracy of the used RFEA. The dependence of the mean ion energy at the grounded electrode does not simply follow the trend of the DC self-bias and the symmetry parameter as a function of the magnetic field (see figure 8). Note that the symmetry parameter is calculated based on neglecting the voltage drop across the plasma bulk. The DC self-bias will correspond to the difference of the time average sheath voltages at the powered and grounded electrode, if the voltage drop across the magnetized bulk region is neglected. However, as the magnetic field increases, the voltage drop across the magnetized bulk region also increases due to the enhanced magnetic resistance as a consequence of the magnetic electron confinement. This voltage drop across the magnetized bulk region increases as a function of the discharge current, which, in turn, depends on the target conditions. For a constant driving voltage amplitude, this effect will lead to reduced sheath voltages. Our measurements of the mean ion energy at the grounded electrode indicate that this effect leads to a decrease of the mean ion energy at the grounded electrode above different magnetic fields depending on the gas mixture. For Ar/O₂, this decrease might be observed at lower magnetic fields compared to pure argon, since the discharge current is higher compared to the pure argon discharge due to the oxidized target surface and the higher secondary electron emission coefficient [14, 51]. Again, simulation and/or modeling studies are required in the future to clarify this. Such studies are not part of this experimental work, which, however, provides the basis for model/simulation verification in the future.
Figure 9. Mean ion energies measured in pure Ar and Ar/O₂ (25 sccm argon + 3 sccm O₂) at the grounded electrode of the geometrically asymmetric RF magnetron (a) and electron densities measured in both gas mixtures at an axial position in the middle of the electrode gap and at a radial position corresponding to the edge of the powered electrode in the geometrically asymmetric RF magnetron (b) 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 \( \vec{B} \) is maximum. Discharge conditions: 13.56 MHz, 1 Pa, 300 V driving voltage amplitude.

Figure 10. Current density measured at the center of the grounded electrode normalized by its respective maximum as a function of time within two RF periods 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: Ar/O₂ (25 sccm + 3 sccm), 13.56 MHz, 1 Pa, 300 V driving voltage amplitude.

Figure 9(b) shows the electron density measured in the axial center of the discharge underneath the radial edge of the powered electrode as a function of the magnetic field in pure argon and in Ar/O₂ for a fixed driving voltage amplitude of 300 V at 1 Pa. These results show that admixing a flow of 3 sccm of oxygen to a flow of 25 sccm of argon does not influence the electron density significantly at this position outside the magnetized region.

In figure 10 the current densities measured by the SEERS sensor at the center of the grounded electrode time resolved within two RF periods in the mixture of Ar/O₂ are shown for different magnetic flux densities. Figure 11 shows the corresponding Fourier spectra. Compared to the current measurements in pure Ar (see figure 5), the unmagnetized case (a) shows a stronger damping of the high frequency PSR current oscillations due to the admixture of a more collisional molecular gas. Correspondingly compared to pure argon, the Fourier spectrum of the unmagnetized case shows more pronounced amplitudes at low frequencies around the driving frequency of 13.56 MHz relative to the high frequency part of the spectrum. For the unmagnetized Ar/O₂ case, a maximum of the Fourier spectrum is observed at 203.4 MHz, which is identified as the PSR frequency. Introducing a magnetic field in the Ar/O₂ case has similar consequences on the current waveform as in pure argon. For a magnetic field of 7 mT, the strong negative extremum of the current density indicates the acceleration of electrons by the expanding sheath at the powered electrode. A second negative extremum occurs for higher magnetic flux densities a few nanosecond after the first peak and its amplitude increases relative to the first negative extremum as a function of the magnetic field similar to the discharge operated in pure argon under otherwise identical conditions (see figure 5). Overall, the magnetic field clearly affects the PSR oscillations of the RF current waveform. Thus, it can be used to control NERH also in mixture of Ar/O₂.

Figure 12 shows the accumulated power dissipated to electrons as a function of time within the RF period calculated from the current waveform based on equation (3) for the Ar/O₂ gas mixture. The results are similar to those obtained for pure argon under otherwise identical discharge conditions (see figure 7). A strong initial increase of the power dissipated to electrons is observed at the beginning of the RF period due
Figure 11. Fourier spectrum of the current density measured at the center of the grounded electrode normalized by the maximum of the Fourier terms 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: Ar/O$_2$ (25 sccm + 3 sccm), 13.56 MHz, 1 Pa, 300 V driving voltage amplitude.

Figure 12. Time resolved normalized accumulated power dissipated to electrons in the geometrically strongly asymmetric reactor operated in Ar/O$_2$ (25 sccm + 3 sccm) 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: Ar/O$_2$ (25 sccm + 3 sccm), 13.56 MHz, 1 Pa, 300 V driving voltage amplitude.

to the sheath expansion heating of electrons at the powered electrode. Due to the presence of the PSR current oscillations plateaus are observed within this initial increase of $P_e$. For low magnetic fields, this initial increase is slightly weaker compared to the pure argon scenario, since the PSR current oscillations are damped more strongly in the presence of a molecular gas admixture. During the second half of the RF period the accumulated power dissipated to electrons increases again during the phase of sheath expansion at the grounded electrode. This increase is stronger for higher magnetic fields, since the discharge is more symmetric at higher magnetic fields (see figure 8(b)) and, thus, sheath expansion heating at the grounded electrode is stronger. Moreover, electron power absorption at the powered electrode during the second half of the RF period might be present due to electric field reversal during the local sheath collapse in the presence of high magnetic fields.

4. Conclusions

The magnetic asymmetry effect (MAE) was investigated experimentally in a strongly geometrically asymmetric capacitively coupled RF magnetron plasma operated at 13.56 MHz and at low pressure (1 Pa) in pure argon as well as an in an Ar/O$_2$ mixture (25 sccm + 3 sccm). Such low temperature plasma sources are highly relevant for thin film deposition via sputtering and are characterized by a strong magnetic field only adjacent to the target electrode, but not at the opposite electrode. The DC self-bias voltage, the plasma symmetry, the time resolved RF current, the plasma density, and the ion flux-energy distribution function at the grounded electrode were measured as a function of the driving voltage amplitude and the magnetic field measured at a reference position. By comparing the experimental results obtained in Ar/O$_2$ to those obtained in pure argon under otherwise identical discharge conditions the effects of adding O$_2$ on the MAE were identified. Similarly, by comparing results obtained in a geometrically strongly asymmetric reactor to those obtained in a reactor with optimized geometrical symmetry under otherwise identical discharge conditions, the effects of the geometric reactor symmetry on the MAE were studied.

The geometric reactor asymmetry was found to prevail over the magnetic discharge asymmetry in the geometrically asymmetric reactor. While adjusting the magnetic field at the target electrode allows to tune the DC self-bias and the discharge symmetry over wide ranges in a geometrically relatively symmetric reactor, this magnetic symmetry control is attenuated in geometrically asymmetric reactors. While the plasma density and the ion flux to the grounded electrode are found to be strongly enhanced as a function of the magnetic field, the mean ion energy increases only slightly at the grounded electrode, since the discharge symmetry and the DC self-bias are not affected significantly by tuning the magnetic field. Increasing
the driving voltage amplitude is found to enhance the DC self-bias and to reduce the plasma symmetry, since the plasma expands towards the grounded chamber walls. For high magnetic fields and high driving voltage amplitudes, the voltage drop across the magnetized plasma bulk region seems to be enhanced due to an increase of the magnetic resistance and the RF current as a function of the magnetic field. This might cause the sheath voltage and, thus, the mean ion energy at the grounded electrode to decrease as a function of the driving voltage amplitude for high magnetic fields. In the strongly geometrically asymmetric reactor, strong high frequency oscillations of the RF current waveform are observed due to the self-excitation of the plasma series resonance (PSR) during the sheath expansion phase at the powered target electrode. These PSR oscillations cause non-linear electron resonance heating (NERH) and are found to be significantly affected by the magnetic field adjacent to the powered electrode. Thus, the magnetic field can be used as a control parameter for NERH.

Admixing 12% O₂ to argon causes an oxidation of the aluminum target surface and an increase of the secondary electron emission coefficient at the powered target electrode [14, 51]. In the unmagnetized low pressure scenario, no effect of adding O₂ on the DC self-bias voltage, the plasma symmetry, and the mean ion energy at the grounded electrode is observed, since the secondary electrons generated at the target electrode and accelerated towards the plasma bulk are not confined to the discharge and do not cause significant ionization at the low neutral gas pressure of 1 Pa. Increasing the magnetic field at the powered electrode, however, leads to a better confinement of these electrons. Due to the higher secondary electron yield in the presence of the O₂ admixture, the plasma is found to be more symmetric in Ar/O₂ compared to pure argon under otherwise identical discharge conditions. The mean ion energy at the grounded electrode is found to follow a complex trend as a function of the magnetic field. This is explained qualitatively by an increase of the voltage drop across the plasma bulk as a function of the magnetic field due to an enhanced magnetic resistance. This bulk voltage drop also depends on the discharge current, which is higher for Ar/O₂ compared to pure Ar due to the higher secondary electron yield. The PSR oscillations of the RF current waveform are found to be damped more quickly in the presence of the more collisional molecular gas. This leads to a small attenuation of NERH during the sheath expansion at the powered electrode.

These experimental findings are expected to play an important role for knowledge based optimization and control of RF magnetron sputtering applications. They yield insights into the fundamental physics of such low temperature plasmas and provide the basis for the experimental verification of future model/simulation studies of RF magnetrons, which could ultimately reveal the charged particle dynamics in such discharges. Industrial sputter applications are typically based on strongly geometrically asymmetric plasma reactors, i.e. the ratio of the powered surface to the grounded surface is small. Higher magnetic flux densities of 100 mT might be required to realize magnetic control of the ion flux-energy distribution at boundary surfaces via the MAE under such discharge conditions. Constructing more geometrically symmetric reactors will also lead to conditions where the MAE is not suppressed by the geometrical asymmetry. In any case, a tunable magnetic field is needed.

Acknowledgments

This work was funded by the German Research Foundation in the frame of the project 'Plasmabasierte Prozessführung von reaktiven Sputterprozessen' (No. 417888799).

ORCID iDs

M Oberberg https://orcid.org/0000-0002-8170-0628
B Berger https://orcid.org/0000-0001-7053-2545
R P Brinkmann https://orcid.org/0000-0002-2581-9894
J Schulze https://orcid.org/0000-0001-7929-5734

References

[1] Amanatides E and Mataras D 2001 J. Appl. Phys. 89 1556
[2] Behzad A, Freilich A and Scholl R 1999 J. Vac. Sci. Technol. A 17 1934–40
[3] Berg S and Nyberg T 2005 Thin Solid Films 476 215–30
[4] Berg S, Särhammar E and Nyberg T 2014 Thin Solid Films 565 186–92
[5] Bora B and Soto I 2014 Phys. Plasmas 21 083509
[6] Bradley J W and Welzel T 2009 J. Phys. D: Appl. Phys. 42 093001
[7] Bräuer G, Szyrza B, Vergöhl M and Bandorf R 2010 Vacuum 84 1354–9
[8] Britun N, Minea T, Konstantinidis S and Snyders R 2014 J. Phys. D: Appl. Phys. 47 224001
[9] Chapman C 1980 Glow Discharge Processes (New York: Wiley)
[10] Christie D J 2005 J. Vac. Sci. Technol. A 23 330–5
[11] Corr C S, Gomez S and Graham W G 2012 Plasma Sources Sci. Technol. 21 055024
[12] Czarnecki U, Mussenbrock T and Brinkmann R P 2006 Phys. Plasmas 13 123503
[13] Czarnecki U, Schulze J, Schüngel E and Donkó Z 2011 Plasma Sources Sci. Technol. 20 024010
[14] Depla D, Haemers J and Gryse R D 2006 Thin Solid Films 515 468–71
[15] Depla D and Mahieu S 2008 Reactive Sputter Deposition (Berlin: Springer)
[16] Depla D, Mahieu S and Gryse R D 2009 Thin Solid Films 517 2825–39
[17] Derzi A, Korolov I, Schüngel E, Donkó Z and Schulze J 2013 Plasma Sources Sci. Technol. 22 065009
[18] Donkó Z, Schulze J, Heil B G and Czarnecki U 2008 J. Phys. D: Appl. Phys. 42 025205
[19] Emmerlich J, Mráz S, Snyders R, Jiang K and Schneider J M 2008 Vacuum 82 867–70
[20] Fiebrandt M, Oberberg M and Awakowicz P 2017 J. Appl. Phys. 122 013502
[21] Franz G and Klick M 2005 J. Vac. Sci. Technol. A 23 917–21
[22] Gahan D, Daniels S, Hayden C, Sullivan D O and Hopkins M B 2011 Plasma Sources Sci. Technol. 21 015002
[23] Gahan D, Dolinaj B, Hayden C and Hopkins M B 2009 Plasma Processes Polyem. 6 5643–8
[24] Gerd T, Cuyett S, Crisan M and Mazouffre S 2013 Plasma Sources Sci. Technol. 22 015024
[25] Godyak V A 1976 Sov. J. Plasma Phys. 2 560
[26] Greene J E 2017 J. Vac. Sci. Technol. A 35 05C204
[27] Gudmundsson J T, Kozinetsov I G, Patel K K and Lieberman M A 2001 J. Phys. D: Appl. Phys. 34 1100–9

[28] Heil B G, Czarnecki U, Brinkmann R P and Mussenbrock T 2008 J. Phys. D: Appl. Phys. 41 165202

[29] Jean M-D, Jiang J-B, Xu M-S and Chien Y 2016 MATEC Web Conf. 71 04005

[30] Kaganovich I D, Kolobov V I and Tsendin L D 1996 Appl. Phys. Lett. 69 3818–20

[31] Kelly P and Arnell R 2000 Vacuum 56 159–72

[32] Kim S, Lieberman M A, Lichtenberg A J and Gudmundsson J T 2006 J. Vac. Sci. Technol. A 24 2025–40

[33] Klick M 1996 J. Appl. Phys. 79 3445–52

[34] Klick M, Eichhorn L, Rehak W, Kammeyer M and Mischke H 1999 Surf. Coat. Technol. 116–119 468–71

[35] Kozinetsov V, Mačák K, Schneider J M, Helmersson U and Petrov I 1999 Surf. Coat. Technol. 122 290–3

[36] Lafleur T, Chabert P and Booth J P 2013 J. Phys. D: Appl. Phys. 46 135201

[37] Lapke M 2011 Analyse und optimierung der multipolresonanzsonde als industrietaugliches plasmadiagnostiksystem PhD Thesis Ruhr-University of Bochum

[38] Lapke M, Mussenbrock T and Brinkmann R P 2008 Appl. Phys. Lett. 93 051502

[39] Lapke M, Oberrasch J, Mussenbrock T and Brinkmann R P 2013 Plasma Sources Sci. Technol. 22 025005

[40] Lieberman M A, Booth J P, Chabert P, Rax J M and Turner M M 2002 Plasma Sources Sci. Technol. 11 283–93

[41] Lieberman M A and Lichtenberg A J 2005 Principles of Plasma Discharges and Materials Processing 2nd edn (New York: Wiley)

[42] Lundin D and Sarakinos K 2012 J. Mater. Res. 27 780–92

[43] Meyyappan M and Colgan M J 1996 J. Vac. Sci. Technol. A 14 2790–4

[44] Mussenbrock T, Brinkmann R, Lieberman M, Lichtenberg A and Kawamura E 2008 Phys. Rev. Lett. 101 085004

[45] Mussenbrock T and Brinkmann R P 2006 Appl. Phys. Lett. 88 151503

[46] Nakano N and Makabe T 1995 Phys. Rev. Lett. 75 283–93

[47] Oberteg M, Engel D, Berger B, Wölfel C, Eremin D, Lunze J, Brinkmann R P, Awakowicz P and Schulze J 2019 Plasma Sources Sci. Technol. 28 115021

[48] Oberteg M, Kallähn J, Awakowicz P and Schulze J 2018 Plasma Sources Sci. Technol. 27 105018

[49] Oda S 1993 Plasma Sources Sci. Technol. 2 26–9

[50] Ohring M 2001 Materials Science of Thin Films (New York: Academic)

[51] Phelps A V and Petrovic Z L 1999 Plasma Sources Sci. Technol. 8 21–44

[52] Popov O A and Godyakov V A 1985 J. Appl. Phys. 57 53–8

[53] Rossnagel S M 2002 J. Vac. Sci. Technol. A 21 S74–87

[54] Saikia P, Bhuyan H, Escalona M, Favre M, Bora B, Kakati M, Wyndham E, Rawat R S and Schulze J 2018 J. Appl. Phys. 123 183303

[55] Samuelsson M, Lundin D, Jensen J, Raadu M A, Gudmundsson J T and Helmersson U 2010 Surf. Coat. Technol. 205 591–6

[56] Schmidt R, Mayrhofer P, Schmid U and Bittrich A 2019 J. Appl. Phys. 125 084501

[57] Schulz C et al 2012 The multipole resonance probe: investigation of an active plasma resonance probe using 3D-electromagnetic field simulations Proc. of the 42nd European Microwave Conf. pp 566–9

[58] Schulz C, Styrnoll T, Storch R, Awakowicz P, Musch T and Rolles I 2014 IEEE Sens. J. 14 3408–17

[59] Schulze J, Donkó Z, Lafleur T, Wilczek S and Brinkmann R P 2018 Plasma Sources Sci. Technol. 27 055010

[60] Schulze J, Donkó Z, Schüngel E and Czarnecki U 2011 Plasma Sources Sci. Technol. 20 045007

[61] Schulze J, Heil B G, Lunzenhölscher D, Mussenbrock T, Brinkmann R P and Czarnecki U 2008 J. Phys. D: Appl. Phys. 41 042003

[62] Schulze J, Kampuschulte T, Lunzenhölscher D and Czarnecki U 2007 J. Phys.: Conf. Ser. 86 012010

[63] Schulze J, Schüngel E and Czarnecki U 2009 J. Phys. D: Appl. Phys. 42 092005

[64] Schulze J, Schüngel E, Czarnecki U and Donkó Z 2009 J. Phys. 106 063307

[65] Schüngel E, Schulze J, Donkó Z and Czarnecki U 2011 Phys. Plasmas 18 013503

[66] Senesky D G and Pisano A P 2010 Aluminum nitride as a masking material for the plasma etching of silicon carbide structures 2010 IEEE 23rd Int. Conf. on Micro Electro Mechanical Systems (MEMS) (IEEE)

[67] Sproul W, Christie D and Carter D 2005 Thin Solid Films 491 1–17

[68] Stoffels E, Stoffels W W, Vender D, Kando M, Krosen G M W and de Hoog F J 1995 Phys. Rev. E 51 2425–35

[69] Styrnoll T, Bielholz S, Lapke M and Awakowicz P 2014 Plasma Sources Sci. Technol. 23 025013

[70] Styrnoll T, Harhausen J, Lapke M, Storch R, Brinkmann R P, Foest R, Ohl A and Awakowicz P 2013 Plasma Sources Sci. Technol. 22 045008

[71] Surenda M and Graves D B 1991 Appl. Phys. Lett. 59 2091–3

[72] Trieschmann J, Shihab M, Szremdey D, Elgendy A E, Gallian S, Eremin D, Brinkmann R P and Mussenbrock T 2013 J. Phys. D: Appl. Phys. 46 084016

[73] Turner M M 1995 Phys. Rev. Lett. 75 1312–5

[74] Turner M M, Hutchinson D A W, Doyle R A and Hopkins M B 1996 Phys. Rev. Lett. 76 2069–72

[75] Vahedi V, Birdsall C K, Lieberman M A, Dipeso G and Rognlien T D 1993 Phys. Fluids B 5 2719–29

[76] Wilczek S et al 2016 Phys. Plasmas 23 063514

[77] Wilczek S, Trieschmann J, Schulze J, Donkó Z, Brinkmann R P and Mussenbrock T 2018 Plasma Sources Sci. Technol. 27 125010

[78] Wilczek S, Trieschmann J, Schulze J, Schüngel E, Brinkmann R P, Derashi A, Korolov I, Donkó Z and Mussenbrock T 2015 Plasma Sources Sci. Technol. 24 024002

[79] Woelfel C, Awakowicz P and Lunze J 2017 IFAC-PapersOnLine 50 13728–34

[80] Woelfel C, Awakowicz P and Lunze J 2017 Tuning rule for linear control of nonlinear reactive sputter processes 2017 21st International Conference on Process Control (PC) (Piscataway, NJ: IEEE)

[81] Woelfel C, Bockhorn D, Awakowicz P and Lunze J 2018 J. Process Control 83 121–8

[82] Yan M and Goedheer W J 1999 Plasma Sources Sci. Technol. 8 349–54

[83] Yang S, Chang L, Zhang Y and Jiang W 2018 Plasma Sources Sci. Technol. 27 035008

[84] Yang S, Zhang Y, Wang H, Cui J and Jiang W 2017 Plasma Processes Polym. 14 1700087

[85] Ziegler D et al 2010 Plasma Sources Sci. Technol. 19 045001