Spatial and temporal development of the plasma potential in differently configured pulsed magnetron discharges

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Abstract. Time-resolved emissive probe measurements have been performed to study the spatio-temporal development of the plasma potential in an asymmetric bipolar pulsed magnetron discharge. The influence of the substrate potential as well as of the substrate position has been investigated while the further conditions were the same. To access the entire potential range which was between $-100 \text{ V}$ and $+400 \text{ V}$ and to obtain sufficient time-resolution of the emissive probe, different heating currents had to be used. The plasma potential has been found to be typically close to zero in the ‘on’ phase, about $+40 \text{ V}$ in the stable ‘off’ phase and up to $+400 \text{ V}$ at the beginning of the ‘off’ phase, which is in agreement with the results of other authors. However, the positive values in the ‘off’ phase are generally lower than those reported and stay mostly below the target potential. This is explained by macroscopic considerations of the quasineutrality of the plasma taking into account a magnetic and geometrical shielding of the target, acting as an anode in the ‘off’ phase, and the potential and position of the substrate holder and environment.
1. Introduction

Magnetron sputtering is an established tool for high rate and large area deposition of high-quality thin films [1]. The structure and properties of these coatings can be controlled by the parameters of the discharge such as the density and energy of the particles, i.e. ions, electrons and neutrals, which interact with the substrate. In many cases it is desired to systematically reduce the energy which is transferred from the plasma to the film, especially when thermally sensitive substrates such as polymers are used. Practical process optimization, however, turns out to be complicated due to many involved species. Recently, pulsed magnetron sputtering discharges have frequently been used, especially when dielectric coatings are to be deposited [2]–[5]. The pulsed operation of the discharge prevents significant charging of insulating films deposited also on the target surface. Consequently, the formation of arcs is suppressed and the discharge is much more stable whereby the quality of the coatings, e.g. their transparency, conductivity and structure, is enhanced [6]. The periodic interruption or reversal of the discharge voltage leads on the other hand to strong temporal changes of the plasma parameters (see e.g. [7]–[14]) which make a physical description even more difficult, and a tailoring of the deposition process for pulsed magnetron sputtering is to date practically impossible.

One of the important plasma parameters is the plasma potential, \( V_{pl} \), in the discharge volume. It determines the electric field which accelerates the electrons to sustain the discharge, and its spatial distribution is therefore crucial for the discharge formation and distribution. On the other hand, the value of the plasma potential in front of each electrode or wall at fixed potential determines the energy with which the ions hit the surface and controls the charge flux to the electrodes. Its knowledge is thus important directly for the film deposition as long as the substrate is not at floating potential which adjusts itself according to the plasma potential and the electron energy.

The plasma potential can be determined using Langmuir single probes (see e.g. [15]). This often applied method is based on the fact that when the probe potential equals the plasma potential the electron current to the probe changes its voltage dependence. At probe potentials below the plasma potential electrons are repelled according to their energy distribution whereas at probe potentials above the plasma potential electrons are drawn from the plasma according.
to their random thermal current and the sheath width. Extrapolating these two regions yields the plasma potential at the junction of both lines. This procedure in many cases gives rather imprecise results due to too ideal assumptions for both potential ranges. Other methods use the first or second derivative of the characteristics to obtain $V_{pl}$, which is difficult with often noisy characteristics. Furthermore, in pulsed discharges where the plasma potential is varying with time, it cannot be accessed with all these methods because the characteristics obtained will be an average over differently shifted $I$–$V$ curves. In such discharges, the plasma potential has to be measured time-resolved by taking probe characteristics at each time within the pulse as done by Bradley and others [11, 16]. Another possibility to determine the plasma potential is the use of an energy-dispersive ion mass spectrometer. Positive ions which are detected against ground have to pass through the potential difference between plasma and ground so that their energy distribution reproduces the plasma potential. Due to the time-of-flight within the spectrometer, the measurement is not time-resolved unless a gating technique is used [17, 18]. Therefore, the assignment of structures in the ion energy distribution function (IEDF) to changes in the plasma potential is not straightforward. However, as demonstrated in [16], temporal changes in the plasma potential can be obtained from the interpretation of the IEDF together with the knowledge of the target voltage trace.

A rather simple alternative is the use of an emissive probe [19]–[21]. The principle is based on an ordinary Langmuir single probe. Through an appropriate heating of the probe tip it emits electrons, which act as an apparent additional positive ion current drawn by the probe from the plasma. The floating potential measured by such a probe thus approaches the plasma potential and serves as a good measure for it—in an ideal case with an error in the order of $kT_p/e$, where $T_p$ is the probe temperature—as soon as the probe temperature is high enough. The advantage of the method is that it is not necessary to acquire the complete characteristics to obtain the plasma potential, rather it can be accessed from a single measurement of the floating potential which is easily obtained through a high impedance measurement against ground. With this measurement being performed with an oscilloscope, a time-resolved determination of varying plasma potentials is possible. The method has been applied to an asymmetric-bipolar pulsed magnetron with a carbon target for a fixed parameter set of 583 W, 0.7 Pa and a duty cycle of 50% by the group of Bradley [22]–[25]. They found a plasma potential close to ground during the whole ‘on’ phase where the target potential is strongly negative. In the ‘off’ phase with the target potential, $V_T$, being positive, positive plasma potentials just above $V_T$ were observed throughout the discharge volume with the plasma potential following a strong positive spike just at the beginning of the ‘off’ phase. The authors conclude that this behaviour is likely to be representative for other discharge parameters. In an earlier work [26], we have found a similar behaviour but could not generally confirm a positive plasma potential with respect to the target potential in the ‘off’ phase.

In this paper, we present time- and space-resolved plasma potential measurements with an emissive probe in a similar setup but with different geometries. Particularly, the substrate holder has been placed at two different positions opposite to the target. To further investigate the influence of the substrate electrode potential it could be either grounded or insulated.

2. Experimental

The experiments were performed in a purpose-build vacuum chamber with a diameter of 300 mm pumped by a system of a turbomolecular and a rotary pump down to a base pressure.
of $3 \times 10^{-4}$ Pa. The working gas used was argon (purity 99.999%) at a pressure of 0.45 Pa. The geometrical setup together with the measured magnetic flux is shown in figure 1. The magnetron equipped with a carbon target of 100 mm in diameter and a grounded anode cup was fixed in a mounting plate at ground potential 31 mm below the anode surface. The anode itself was located at a distance between 3 and 7 mm above the target surface and had an inner diameter of 90 mm. Opposite the target the substrate holder (diameter 125 mm) was situated at a target-to-substrate distance of either 80 or 150 mm. It was mounted on another grounded plate at a distance of 140 mm from the target which surrounded it (cf figure 1). The substrate holder was electrically isolated from the grounded mounting plate. An external connection allowed to ground or float the substrate holder at both distances. The magnetron was powered by a Pinnacle Plus (Advanced Energy)-pulsed power supply which was operated in constant power mode. Throughout the experiments, a constant power of 400 W was used with a pulse frequency of 100 kHz, and the duty cycle, i.e. the ratio between pulse ‘on’ to total pulse duration, was 0.6. In one particular case, a frequency of 50 kHz and a duty cycle of 0.8 were utilized. The anode of the power supply was connected to the grounded anode cup. Thus the discharge was operated in asymmetric-bipolar mode with the positive target potential in the ‘off’ phase being above ground potential with a value of about 10% of the average negative potential in the ‘on’ phase.

The emissive probe was constructed of a thoriaed tungsten wire of 50 $\mu$m diameter and a length of about 10 mm, which was formed into a closed loop. At its ends, it was clamped...
within tungsten connecting wires of 500 µm diameter, which were housed in quartz tubes to be isolated from the plasma and allowed contact of only the thin probe with the plasma. The whole system was fixed on a holder which was mounted on a linear-rotary feed-through to achieve radial and axial movement within the discharge volume. The loop was oriented parallel to the target surface resulting in an axial resolution of 2 mm and a radial resolution of about 6 mm. The scan of the discharge cross section was performed in axial steps of $\Delta z = 8$ mm from $z = 12$ mm to $z = 68$ mm or $z = 12$ mm to $z = 132$ mm distance from the target for a substrate distance of 80 or 150 mm, respectively. For each axial distance the discharge was radially scanned between $x = -49$ mm and $x = +49$ mm in steps of $\Delta x = 7$ mm. Additional experiments were done with a slightly modified probe holder to allow a closer approach to the target. In this case, the quartz tubes were slightly bent towards the target so that they could be moved over the anode cup, while the probe tip itself was below the anode surface. With this setup, a distance of the probe from the target down to 4 mm was obtained. However, due to the bending the loop was not aligned parallel with the target surface in this case, resulting in a poorer axial resolution of about 4 mm.

The electrical setup of the emissive probe is shown in figure 2. The probe was heated with an insulated dc heating circuit which consisted of a battery (max 15 V and 1.5 A) in series with a variable resistor of max 47 Ω to adjust the probe heating current. The typical voltage at the probe connectors was 3.5 V which gave a current of 0.7 A. Two 47 Ω resistors were connected parallel with the probe and the probe potential was taken between them to minimize the falsification by the longitudinal potential drop along the probe tip. Therefore, the accuracy of the absolute value of the time-resolved plasma potential is about 3 V. The relative error during the scans, i.e. the reproducibility, has been 1 V in the stable phases and about 5 V during transient phases of the discharge. The time-dependent voltage signal of the emissive probe was recorded via a 1:10 voltage divider (Iwatsu SS-0130P, 100 MHz) with a digitizing oscilloscope (Tektronix, TDS 620B). The battery as the heating source was selected to minimize the capacitance of the system to ground ($C_g$) given in figure 2, which strongly influences the time resolution. In the final setup, a capacitance to ground of about 130 pF has been achieved.
Figure 3. Potential traces measured with the emissive probe (top) for three different conditions: (blue) strongly heated at \((x, z) = (21 \text{ mm}, 12 \text{ mm})\), (red) strongly heated at \((x, z) = (28 \text{ mm}, 68 \text{ mm})\), (green) moderately heated at \((x, z) = (28 \text{ mm}, 68 \text{ mm})\). The temporal development of the target potential with the indication of the ‘on’ and ‘off’ phases is given in the bottom diagram.

3. Results

3.1. Experimental procedure

Three examples of the time dependence of the potential measured by the emissive probe are shown in figure 3. They were obtained at different positions in the discharge and with differently strongly heated probe tips. The potential of the probes that were strongly heated shows a significant spike of up to +400 V at the beginning of the ‘off’ phase which temporally coincides with a high positive potential at the target which is obtained just as the target voltage is reversed to positive values (see figure 3). Subsequently to the peak, both probe and target potential decrease to lower positive values. As soon as the target potential is switched to negative values in the ‘on’ phase, the probe potential also decreases and approaches values close to zero. Close to the target, slightly negative values are measured. Generally, at phases with decreasing target potential the probe potential reacts rather slowly away from the target and when the probe is strongly heated.

The response time of the probe circuit is given by \(\tau = R_{sh}Z_{sh}/(R_{sh} + Z_{sh}) \cdot C_g\) [24], where \(R_{sh}\) and \(Z_{sh}\) are sheath resistance and the capacitive sheath impedance, respectively, and \(C_g\) is the capacitance of the circuit to ground which we have measured as 130 pF. The sheath resistance may be expressed as the voltage drop across the sheath over the current through the sheath. The capacitive sheath impedance is \(1/(\omega C_{sh})\) with \(C_{sh} = \varepsilon_0 A/d\), \(d\) being the sheath width and \(A\) the probe area. Taking a potential drop of the order of \(kT_e/e\), a current of the order of the random thermal electron current, and a sheath width of the order of the Debye length \((\varepsilon_0 \cdot kT_e/(e^2n))^{1/2}\), we can roughly estimate the response time. The frequency \(\omega\) of the fast changes in the potential is about 50 MHz. Then a response time in front of the target in the
magnetic trap of \( \sim 10 \text{ ns} \) (taking \( n = 5 \times 10^{11} \text{ cm}^{-3} \) \cite{27}, \( T_e = 5 \text{ eV} \)) and in front of the substrate of \( \sim 500 \text{ ns} \) (taking \( n = 5 \times 10^9 \text{ cm}^{-3} \) \cite{28}, \( T_e = 2 \text{ eV} \)) is obtained, which is of the order of magnitude that we observed (cf figure 3). Importantly, it should be noted that the estimation shows that the response time is strongly dependent on the charge carrier density \( n \) of the local plasma.

At phases where the plasma potential is falling rapidly, electrons delivered from a strongly emitting probe may be repelled from the plasma, which becomes more negative than the emitting probe. Karkari et al \cite{22} suggest that the electrons then form a negative space charge around the probe, which impairs the current through the sheath. Such increased sheath resistance reduces the response time further. Strong emission hence can falsify the values in the stable phases. This can be seen in figure 3 where a strongly and a weakly emitting probe have been used under otherwise same conditions. On the other hand, the spike at the beginning of the ‘off’ phase which coincides with that in the target potential can only be measured with a strongly emitting probe, which is in agreement with the findings of other authors \cite{24}. Intermediate heating is sufficient for the other times during the pulse.

This is shown in more detail in figure 4. Here, the potential obtained from the emissive probe is displayed as a function of the heating current which is a measure of the hardly accessible probe temperature. Three different times during the pulse have been selected: the end of the ‘on’ and of the ‘off’ phase where the changes in the target potential are small and the beginning of the ‘off’ phase where the spike was observed. When the probe starts to emit a sufficient number of electrons, the apparent floating potential measured by the probe increases and approaches the plasma potential. As soon as the plasma potential at a given time is reached, the apparent floating potential saturates and a further increase of the heating current only leads to a very small increase of the order of \( kT_e/e \) \cite{29} which is due to space charge effects. The plasma potential has been obtained from this saturation value without correction of the space charge effects. For the stable periods of time in the ‘on’ and ‘off’ phases, a heating current of 0.55 A was sufficient. However, to saturate the probe potential during the potential spike, much higher heating currents of more than 0.8 A were required (cf figure 4).

Due to the worse time resolution and the short lifetime of the strongly emitting probe, the scans of the cross section were divided into two series. Very hot probes were only used for the determination of the spike at the beginning of the ‘off’ phase and were renewed for each radial scan. The other times were measured with moderately heated probes which allowed the complete scan with one probe. Four particular times during the pulse were investigated: the minimum in the ‘on’ phase, the stable ‘on’ phase, the stable ‘off’ phase, and—with the very hot probe—the beginning of the ‘off’ phase.

3.2. ‘On’ phase

In figure 5, the distribution of the plasma potential during the ‘on’ phase is shown with the substrate holder at the 80 mm distance position. The distribution at the end of the ‘on’ phase (bottom of figure 5) resembles what could be expected for a dc magnetron. With the substrate holder at ground potential, the plasma potential in the bulk plasma, i.e. above the magnetic null of the unbalanced magnetron, is slightly positive. With the substrate at floating potential, the plasma potential in the bulk plasma is significantly lowered and a stronger radial inhomogeneity is observed which images the magnetic field distribution.
Figure 4. Apparent floating potential as a function of the heating current through the probe wire which was considered to be representative of the probe temperature, for different selected moments during the pulse. At each moment, the plasma potential is obtained when the apparent floating potential saturates. (For these measurements a different pulse frequency of 50 kHz and duty cycle of 0.8 were utilized.)

In the early moments of the ‘on’ phase, the target voltage passes through a strong voltage minimum (cf figure 3) which reached $-1250$ V. This has a significant influence on the momentary plasma potential throughout the whole discharge volume as shown in the upper part of figure 5. Except on the edges of the discharge, where the plasma potential is almost unaltered, the values of the plasma potential are decreased also, resulting in a stronger inhomogeneity. Even when the substrate is grounded, slightly negative plasma potentials of $-1$ V are observed close to the substrate. In the magnetic trap, the plasma potential temporarily drops to $-45$ V compared with $-25$ V for the stable ‘on’ phase for both substrate potentials investigated.

Figure 6 shows the plasma potential distribution at the end of the ‘on’ phase for two distances of the substrate holder. Also included are measurements performed close to the target at 4 mm distance. At these distances the plasma potential is strongly negative as the probe position is deeper in the pre-sheath. The minimum values agree quite well with $-40$ V and $-36$ V for the 80 mm and 150 mm distances. Like the potential of the substrate (cf figure 5) this demonstrates again that the geometrical and electrical conditions away from the target do not much influence the potential structure close to the target. However, there are apparent differences in the potential of the bulk plasma extending to the substrate which in both cases is held at floating potential. When it is located 80 mm from the target, the plasma potential stays below zero along the centre line with about $-8$ V close to the substrate. With a distance of 150 mm (see figure 6(b)) the potential distribution is flattened 40 mm above the target and the absolute values are closer to zero. This potential distribution looks more like that for a grounded substrate (cf figure 5(d)) than a floating one. In fact, the potential distribution measured at the same geometry as in figure 6(b) but with the substrate holder grounded (not shown here) is almost the same as in figure 6(b).
3.3. Stable ‘off’ phase

The plasma potential distribution at the end of the ‘off’ phase is shown in figure 7 for the target-to-substrate distance of 150 mm. Generally, $V_{pl}$ at this time is positive slightly above +40 V, a fact that has also been found by other authors [22]–[25]. The plasma potential in discharges typically adjusts close to the potential of the most positive electrode. In the ‘off’ phase of the asymmetric-bipolar pulsed discharge this electrode is the target, which had a momentary potential of $+68 \cdots +69$ V in the present case while anode cup and walls act as cathode where most of the potential drop occurs. Most interestingly, we always observe plasma potentials which are, although positive, below the target potential at the end of the ‘off’ phase. There
Figure 6. Plasma potential distribution at the end of the ‘on’ phase of the pulsed discharge with a floating substrate: (a) represents the situation with the substrate at a distance of 80 mm from the target ($V_T = -600$ V), (b) represents a distance of 150 mm ($V_T = -560$ V). Note that the data at $x = \pm 49$ mm and $z = 4$ mm could not be measured because of geometrical restrictions and are displayed at zero potential.

Figure 7. Plasma potential distribution during the stable ‘off’ phase of the pulsed discharge with a substrate distance of 150 mm from the target: (a) substrate floating ($V_T = +68$ V) and (b) substrate grounded ($V_T = +69$ V).

is a slight drop in the plasma potential from the target to the substrate at 150 mm of about 3 V for both substrate potentials, resulting in a very weak electric field of 25 V m$^{-1}$ pointing towards the substrate. The small potential changes result in a humpy distribution corresponding to the relative uncertainty of the measurements of about 1 V. Comparing the potential distribution for the floating (figure 7(a)) with that of the grounded (figure 7(b)) substrate, a shift of 1–2 V in the absolute values is clearly seen.
Figure 8. Plasma potential distribution during the positive peak in the target voltage (about +340 V) at the beginning of the ‘off’ phase with a substrate distance of 150 mm from the target: (a) substrate floating and (b) substrate grounded.

The same behaviour has been observed for a substrate distance from the target of 80 mm (not shown here). The plasma potential dropped from the target region to 68 mm by about 2 V and was on average 1 V lower in the grounded case. Again, the plasma potential was below the target potential.

3.4. Beginning of the ‘off’ phase

Figure 8 shows the plasma potential distribution at the beginning of the ‘off’ phase for a target-to-substrate distance of 150 mm. Generally, the plasma potential exhibits strongly positive values throughout the discharge volume. The highest values are measured close to the positive target with the magnetic trap being clearly reflected in the potential distribution by a particularly high plasma potential. Both figures show that the plasma potential immediately follows the strong rise of the target potential so that it stays close to the potential value of the target. This fact confirms the observation of others [22]–[25]; however, because of the different discharge geometries it is not possible to establish a general rule yet. The potential distributions have also been measured for a substrate distance of 80 mm and confirm those in figure 8. They particularly proved that $V_{Pl}$ is always slightly lower (10 V) in the bulk for the grounded substrate compared with the floating one.

The structures which seem to be present in figure 8 within the bulk of the plasma resulting in some local minima along the axis of symmetry, especially the apparent minimum around $z = 50$ mm, are an artefact of the target potential fluctuations in the spike during the time-consuming measurements with the very hot probe.

4. Discussion

The plasma potential distribution can be determined from the Poisson relation

$$\varepsilon_0 \cdot \Delta V_{Pl}(\vec{r}) = e \left[ n_e(\vec{r}) - n_i(\vec{r}) \right],$$

(1)
(\varepsilon_0, \text{dielectric constant}; e, \text{elementary charge}; n_e, \text{electron density}; n_i, \text{(positive) ion density}). To calculate the distribution in the pulsed magnetron, the spatial density distributions of the electrons and ions have to be known for each moment during the pulse in combination with boundary conditions for the electric field and the potential. Considering the extremely inhomogeneous discharge, this is almost impossible to solve analytically. Instead, a macroscopic approach which is based on the quasineutrality of the plasma shall be used to understand the temporal and spatial behaviour of the plasma potential in the pulsed magnetron discharge. For any given homogeneous discharge in the stationary state, the flux of ions to the cathode has to be compensated by an equal electron flux to the anode. In a pulsed magnetron the situation is more complicated because of rapid temporal changes and the strong inhomogeneity of the discharge but the general requirement holds that no net charge should be extracted.

During the ‘on’ phase of the discharge ions are extracted from the plasma with the Bohm flux [30]

\[ J_i = 0.61 \cdot e \cdot n_i \cdot \sqrt{\frac{kT_e}{m_i}}, \]

\( k, \text{Boltzmann constant}; m_i, \text{ion mass (Ar)}; T_e, \text{electron temperature, taken to be } kT_e/e = 5 \text{ V} \) to the target but due to the strongly negative potential no electrons flow to the target. Taking a local argon ion density \( n_i \) in front of the target of the order of \( 5 \times 10^{11} \text{ cm}^{-3} \) and assuming that due to the very inhomogeneous discharge only half of the target effectively collects ions, one obtains an ion current of about 0.7 A which is a typical value for our magnetron. Then, the same current of electrons has to flow to the grounded parts of the setup. The closest of those is the anode cup, which would require significant cross-field drift to the magnetic field to be reached. Thus, the grounded substrate acts as the main drain for electrons which, without potential barrier, would be subject to the random thermal electron current

\[ J_e = \frac{1}{4} \cdot e \cdot n_e \cdot \sqrt{\frac{8kT_e}{\pi m_e}}, \]

\( m_e, \text{electron mass} \). Taking \( n_e \) of the order of \( 5 \times 10^9 \text{ cm}^{-3} \) and \( T_e = 2 \text{ eV} \), an electron current of 2.3 A can be calculated. This is much more than the ion current to the target. To keep quasineutrality, the electron current must be reduced by a potential barrier \( V_{Pl} - V_S \) to equalize the ion current leading to

\[ V_{Pl} - V_S = \frac{kT_e^{(A)}}{e} \ln \left[ \frac{n_e^{(A)} A^{(A)}}{0.61 \cdot n_i^{(C)} A_{eff}^{(C)} \left( \frac{m_i T_e^{(A)}}{2\pi m_e T_e^{(C)}} \right)^{1/2}} \right], \]

where \( A \) and \( A_{eff} \) are the collecting areas and the superscripts \((C)\) and \((A)\) refer to the cathode and the anode, respectively. Taking the above example, a potential barrier of about 2.5 V is necessary. This is in good agreement with the measurement shown in figure 5(d). Close to the target, secondary electrons which are released from the target are confined in the magnetic trap, mostly above the race track. This locally trapped excess negative charge that is prevented from reaching the anode lowers the potential \( V_{Pl} \) in this region which becomes strongly negative (cf figure 5).

When the substrate is instead at floating potential and does not drain any net current, the electrons have to move to the grounded mounting plate around the substrate to close the
circuit. However, most of the magnetic field lines of the unbalanced magnetron terminate on the substrate holder when it is at 80 mm distance so that an effective electron drain to the mounting plate is prevented. This results in much lower values for the plasma potential than for the grounded substrate at 80 mm (cf figure 5(c)).

The situation is different when the substrate holder is at 150 mm distance, in the plane of the mounting plate (cf figures 6(a) and (b)). The magnetic field is diverging for distances above 70 mm from the target (cf figure 1). Without the floating substrate holder in the way, more electrons can thus reach the grounded plate and cause a net electron drain. Consequently, the plasma potential is raised and is comparable with the situation with the grounded substrate at 80 mm (see figure 5(c)). An additional grounding of the substrate holder at 150 mm only leads to a small further increase of the plasma potential (+1.6 V) as it has already been attached to the grounded plate.

About 1 µs after the start of the ‘on’ phase, the target voltage has a strong overshoot about twice as much as at the end of the ‘on’ phase (−1250 V versus −600 V). At this moment, more secondary electrons are released from the target surface into the discharge volume and lower the plasma potential as an excess negative charge (see figures 5(a) and (b)). The effect is recognized within the whole discharge volume with a delay of only 250 ns (see figure 3). This delay is caused by the ions which have to cross the sheath before they can release more electrons due to their higher energy. The temporal plasma potential decrease is strongest close to the target because most of the additional secondary electrons are trapped above the race track. The weaker decrease in the bulk is caused by electrons that either start at field lines extending to the substrate region or are scattered onto them. There is no detectable difference in the delay between the two regions because an electron which is accelerated by 1250 V will travel 20 cm within only 10 ns.

During the ‘off’ phase with a positive target voltage, the potential relations are reversed. The target then acts as the anode of the discharge and any grounded surface adjacent to the plasma acts as cathode. For simplicity, at first we consider the unrealistic case that only the target shall act as an electrode and the walls are imagined as being too distant and draw only a negligible current. The target would then have to be subjected to an equal electron and positive ion flux to keep up quasineutrality and the plasma potential would adjust positive to \( V_T \) to obtain this. Such a behaviour was reported by the group of Bradley [22]–[25], who also concluded that the plasma potential should always be above the target potential. We have, however, observed the plasma potential being consistently lower than \( V_T \) in the stable ‘off’ phase. To explain this, we have to consider the substrate/walls and the magnetic field configuration at the target. If a grounded substrate is present, it will be subject to a net ion current according to equation (2) that has to be compensated by a net electron drain to the target. Compared with the hypothetical situation above, the plasma potential is then lowered to allow this increased electron current. Because the random thermal current density of the electrons is typically much larger than the ion current density, \( V_{pi} \) is still close to the potential of the most positive electrode (here the target) but its absolute value is dependent on the geometrical conditions [31]. A small cathode (grounded surface) or a large anode (target surface) leads to a high plasma potential, whereas a large grounded surface or a small target results in a lower plasma potential. Moreover, the effective electron collecting target area will be dependent on the magnetic field. Electrons from the plasma bulk which provides the majority of the discharge volume are prevented from entering the region of the magnetic trap. Because of our unbalanced magnetron, they will be deflected to the outer edge of the magnetron. Given the configuration of our anode cup which intersects the majority of those field lines, the electrons will mostly be reflected. This results
Figure 9. Distribution of the plasma potential from figure 8 reduced by the actual target potential value taken at each point: (a) substrate floating and (b) substrate grounded.

in a small effective area of the target in our case which leads to a low plasma potential: while others [22]–[25] report about a plasma potential of 2 V [23, 25] or 4–5 V [24] above $V_T$ at the end of the ‘off’ phase, we thus found a plasma potential 28 V below $V_T$. This is reasonable because in the references no or only a small substrate holder is described and the target with a diameter of 150 mm has more than twice our area and no intersecting anode cup.

Because the electron current limitation to the magnetically shielded target determines the plasma potential in the stable ‘off’ phase, the substrate holder potential is only of little influence (cf figure 7). The plasma potential is 1 V lower with a grounded substrate compared with a floating one because the net ion collection area is increased. This necessitates an increased electron current to the target and thus a decreased plasma potential.

Because the plasma potential has been found to always adjust close to the most positive electrode, it is very sensitive to changes of the positive target potential in the ‘off’ phase. To exclude the influence of any drift of the target voltage, the actual value of $V_T$ which was measured simultaneously has been subtracted from the measured $V_{Pl}$. The result is given in figure 9, where the deep valley from figure 8(a) and the dips from figure 8(b) have almost completely vanished, proving that these structures were indeed an artefact of random $V_T$ changes. However, especially the high positive values close to the target remain. These result from a depletion of electrons as soon as the target voltage is reversed to positive values and electrons are immediately accelerated to the target. This process is most effective in the magnetic trap as all magnetic field lines from this region terminate on the target surface. It creates a high electron current of several amps on the target and leaves an excess positive charge. The plasma potential in the rest of the discharge is also temporarily raised. This is particularly the case close to the axis of symmetry where the unbalanced magnetic field still has some field lines that terminate on the target so that a drift along them leads to a drain of electrons. Again, we observe that the plasma potential in the bulk does not or not significantly rise above the target potential, which we again attribute to the strongly magnetically shielded target in our case. As for the stable ‘off’ phase the plasma potential with the grounded substrate is slightly lower.
than with the floating one due to additional ion extraction to the substrate holder. Although the
duration of the spike is very short (about 100 ns) and potential changes will mainly affect the
electron movement to the target, the first ions arrive at the opposite surface allowing an increased
electron current to the target by a slightly reduced plasma potential which is more effective with
the grounded substrate. Plasma potentials much lower than the target potential are measured at
the radial edges. At these positions no drift of the electrons to the target along magnetic field
lines is possible and no rapid drain in the early moments of the ‘off’ phase occurs.

5. Conclusions

An asymmetric-bipolar pulsed magnetron discharge has been investigated with two different
target-to-substrate distances and with the substrate at floating and ground potential for both
geometries. The plasma potential distribution has been measured time-resolved with an emissive
probe. The plasma potential in the ‘on’ phase attains values close to ground throughout almost
the whole discharge volume. In the ‘off’ phase, it is permanently positive while it follows the
target voltage, adjusting itself close to it. It therefore amounts to several 10 V in the stable
‘off’ phase and up to several 100 V at the beginning of the ‘off’ phase. In general, these results
confirm those found previously by others for a single set of parameters in a slightly different
pulsed magnetron. The most significant difference in our case is that the plasma potential in the
‘off’ phase stays below the target potential, which is explained by the geometry and the concept
of quasineutrality for the stationary state.

In the stable ‘on’ phase with the substrate holder close to the target the plasma potential
stays below zero on-axis when the substrate is insulated but slightly above ground when it is
grounded. In the latter case, the electron current to the substrate has to be limited by a potential
barrier to keep on the same value as the ion current to the target. When the substrate distance
is increased, the grounded mounting plate determines the electron current and the potential
distribution. During the very negative overshoot in the target voltage, the plasma potential in
the magnetic trap and the centre of the plasma bulk is always lowered by a few volts due to
temporary excess electrons.

At the end of the ‘off’ phase, the plasma potential is positive but stays below the target
potential. The reason is that the substrate holder and/or mounting plate is draining ions from
the plasma but the electron current to the positive target is hindered by the anode cup of the
magnetron which intersects magnetic field lines together with our comparably small magnetron
area. Therefore, a smaller potential barrier is required and the plasma potential is rather low.

At the beginning of the ‘off’ phase, when the target potential is temporarily (for only about
100 ns) at about + 400 V, electrons are immediately extracted from the region of the magnetic
trap with its magnetic field lines terminating at the target. As a consequence, the plasma potential
in the region even rises above the high target potential. In the rest of the discharge, especially
along the centre line, it is also elevated by the quick electron extraction, but again keeps below
the target potential.

The temporal response of the emissive probe is strongly improving with increasing charge
carrier density. It was significantly worsened at strong heating because of reflection of the
emitted electrons at the plasma boundary at decreasing plasma potential. However, strong
heating is necessary to detect the peak at the beginning of the ‘off’ phase.
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