

Deposition rate and energy to substrate in chopped and standard HiPIMS: identifying optimal pulse parameters

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Abstract. High-Power Impulse Magnetron Sputtering (HiPIMS) offers higher ionized flux fractions at the cost of lower deposition rates compared to conventional DCMS. A fine optimization of the deposition conditions is crucial for specific applications. Chopped or multi-pulse HiPIMS (segmenting pulses into shorter micropulses) has been proposed to mitigate ion back-attraction and promote working gas recovery. This study investigates how micropulse length, delay time between segments, and magnetic field strength influence energy flux, deposition rate, and ionized flux fraction in chopped and standard HiPIMS. These quantities are evaluated by passive thermal probe, biasable QCM and mass spectrometer measurements at the substrate position. Deposition-averaged and pulse-averaged power is kept constant for all conditions to facilitate meaningful comparison.

Results indicate that chopping the HiPIMS pulse consistently leads to higher energy flux and total deposition rate compared to standard HiPIMS at the same total pulse length, primarily due to increased ion flux. A weaker unbalanced magnetic field configuration enhances deposition rates and ion transport. In chopped HiPIMS, increasing micropulse length decreased energy flux and deposition rates, whereas increasing the delay time between micropulses substantially improved these parameters. Importantly, standard HiPIMS, which operated at higher frequencies and short pulse lengths, demonstrated superior performance (with higher total energy and particle fluxes) than chopped HiPIMS when compared at similar short pulse durations. This suggests that consistent short pulse durations and sufficient off-times for complete gas refill are paramount for maximizing ion fluxes and deposition rates.

Keywords: High power impulse magnetron sputtering, Chopped HiPIMS, Energy flux, Ion flux, Deposition rate, Magnetic field

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1. Introduction

High-Power Impulse Magnetron Sputtering (HiPIMS) is an advanced sputtering technique that has gained considerable attention due to its ability to generate dense plasma by applying high-power in short-length pulses with a low-duty cycle [1]. This approach results in a higher degree of ionization of the sputtered material compared to conventional direct-current magnetron sputtering (DCMS). The resulting benefits include the deposition of dense, well-adhered films and improved conformity on complex substrate geometries [2–4].

Despite all the advantages, HiPIMS commonly exhibits a lower deposition rate compared to DCMS when operated at the same average power. The decrease in deposition rate is mainly associated with the return of ionized sputtered species to the target and other effects connected with the depletion of the working gas [5]. This drawback has become a focal point of innovation in reimagining the pulse architecture of HiPIMS to enhance the deposition rate and ion flux fraction toward the substrate while preserving the desirable characteristics of HiPIMS-deposited films.

One such approach involves chopping a standard HiPIMS pulse into multiple micropulses [6–11]. The short off-times facilitate the escape of ionized species from the target vicinity due to the absence of a strong electric field and partial recovery of the local process gas concentration [6, 12, 13], while still preserving the plasma conditions necessary for stable ignition of subsequent micropulses. As reported in our earlier work on multi-pulse bipolar HiPIMS [14], unipolar chopped HiPIMS yields higher energy fluxes compared to standard HiPIMS operated at the same average power and total pulse length.

While the chopped-pulse strategy has demonstrated improvements in deposition rate and ion flux fraction, the mechanisms behind these enhancements remain unclear. The parameter space in HiPIMS is quite broad, and published studies often employ different operating conditions and pulse chopping strategies. As a result, their findings are not easily comparable or generalizable. While the average power (in the period) is typically held constant, the total pulse length or the average pulse power (averaged over the total on-time) are often varied. These differences can significantly impact the discharge plasma and the resulting film

growth conditions, particularly with respect to the ionization degree. Additionally, in our view, it is still unclear whether the presented benefits of chopped HiPIMS are specifically due to the pulse architecture or simply result from operating in a shorter-pulse regime.

In this study, our objective was to deepen the understanding of chopped HiPIMS by systematically investigating how variations in the length of the micropulses, the delay time, and the magnetic field strength influence the deposition characteristics (energy flux, deposition rate, and ionized flux fraction of target material species) at the substrate position. To ensure meaningful comparisons and maintain a consistent ionization degree across all experiments, both the average power and (average) pulse power were kept constant for all configurations, which is not commonly emphasized in earlier investigations. In parallel, variations in pulse length and repetition frequency in standard HiPIMS (without pulse chopping) were also explored to provide a critical evaluation of the effectiveness of the two approaches. A combination of diagnostic tools was employed: a passive thermal probe and a QCM ion flux meter to measure the total energy and the sputtered metal atom and ion fluxes to the substrate, respectively, and a mass spectrometer to separately quantify singly and doubly ionized titanium and argon species at the same location as the probes. These complementary measurements provide detailed insight into the plasma characteristics during chopped and standard HiPIMS operation. This understanding is critical for the optimal application of HiPIMS in film deposition.

2. Experimental details and methodology

The experiments were conducted in a stainless-steel vacuum chamber constructed from DN200ISO-K six-way cross tubing (Fig. 1a). The chamber was equipped with a planar circular magnetron (VT100, Gencoa) with a tunable magnetic field, fitted with a 4-inch titanium (Ti) target. A turbo-molecular pump backed by a scroll pump maintained a base pressure of 4×10^{-4} Pa.

2.1. Magnetic field configurations

The magnetic field configuration is governed by the distances of the center (C) and edge (E) magnets relative to the target surface. When both magnets

are positioned at the closest possible distance (C0E0), the magnetic field is strong and highly unbalanced, resulting in strong plasma confinement above the racetrack, but also guiding the ions from the magnetron edges towards the substrate. Increasing the edge magnet distance to 5 mm, while keeping the center magnet closest (C0E5) reduces this imbalance, reducing the ion fluxes to the substrate. Further increasing the edge magnet distance to 10 mm (C0E10) yields a balanced magnetic field configuration. When both magnets are moved 5 mm away from the target (C5E5), the magnetic field is unbalanced, similar to C0E0, but with a reduced strength, resulting in weaker plasma confinement above the racetrack compared to C0E0. For the series of measurements in which the magnetic field was not varied, we used the C5E5 configuration. A representation of the magnetic field lines for similar configurations can be found in our earlier work [15].

2.2. Pulse configurations

The magnetron was operated in standard HiPIMS and chopped HiPIMS modes using a custom-built pulsing unit powered by a DC power supply (GS10, ADL) and controlled by a waveform generator (Rigol DG4102). Argon (Ar) was used as the working gas at a pressure of 1 Pa, with a constant flow rate of 40 sccm. The target current was monitored using a current probe (TCP303, Tektronix), and the target voltage was measured using a high-voltage probe (TESTEC, 100 $\times$ attenuation). All signals were recorded using a digital oscilloscope (Picoscope 5444D, Pico Technology), which enabled precise determination of the power.

The average power delivered during the pulses (average pulse power) was maintained at 40 kW. The standard HiPIMS pulse is defined by the total pulse length and repetition frequency. The reference standard HiPIMS was operated with 130 μ s pulse length and 96 Hz frequency. The chopped HiPIMS pulse configuration is defined using three parameters and denoted as $5(S_1, S_O, D)$, where 5 is the number of segments (fixed in this work), S_1 is the length of the first pulse segment, S_O is the length of the other four segments, and D is the delay time between segments, resulting in a total of five sequential pulses per cycle. The first micropulse is intentionally chosen longer to assist with plasma initiation, while the subsequent micropulses are shorter. The average power was always 500 W. When the total pulse length was varied, the frequency was adjusted accordingly to maintain both the pulse and the average power at the specified values.

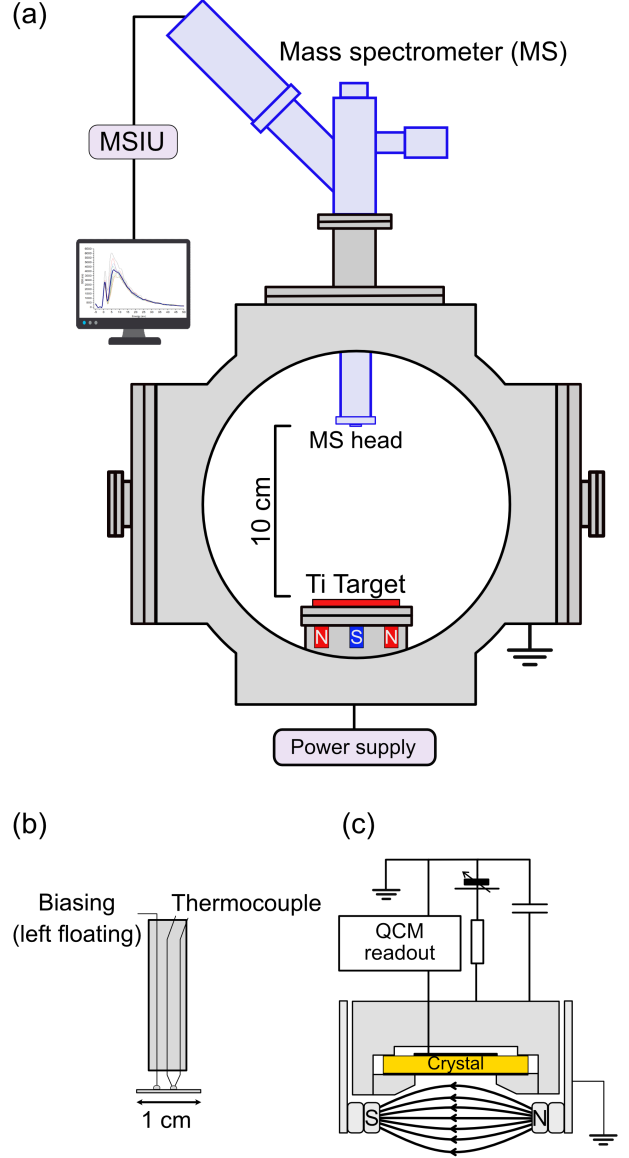


Figure 1. (a) Schematic of the experimental setup with a mass spectrometer (MS). (b) Passive thermal probe with an integrated thermocouple used for temperature measurements and a separate for external bias connection (left floating). (c) QCM ion meter with an external magnetic field, which prevents electrons from reaching the QCM crystal. The mass spectrometer head has been raised to accommodate either the thermal probe or the QCM ion meter at the same distance from the target.

2.3. Substrate flux characterization

To estimate the total energy flux from the plasma to the substrate, a passive thermal probe, operated in floating mode, was placed 100 mm in front of the target (Fig. 1b). The energy input to the probe was derived from the rate of temperature change during plasma-on and plasma-off phases according to:

$$Q_{\text{in}} = C_p \left[\left(\frac{dT_p}{dt} \right)_{\text{heat}} - \left(\frac{dT_p}{dt} \right)_{\text{cool}} \right], \quad (1)$$

where Q_{in} is the energy flux transferred to the probe, C_p is the heat capacity of the thermal probe, $\left(\frac{dT_p}{dt} \right)_{\text{heat}}$ is the rate of temperature increase during the plasma-on phase, and $\left(\frac{dT_p}{dt} \right)_{\text{cool}}$ is the rate of temperature decrease during the cooling phase after plasma shut-off. It is important to note that the energy flux comprises contributions from all plasma species, including Ar atoms and ions, Ti atoms and ions, as well as electrons. A detailed description of the thermal probe design, operation, and post-processing methodology can be found in [14].

A quartz crystal microbalance (QCM) ion meter was employed to measure the mass flux of deposited species (Fig. 1c), namely Ti atoms and ions. It is based on the standard front-loaded QCM sensor (Inficon), positioned 100 mm from the Ti target and facing the target center. To suppress electrons reaching the front of the QCM and the crystal, a pair of cylindrical SmCo magnets (10 mm in length and 8 mm in diameter) was mounted beneath the QCM, forming a localized magnetic field parallel to the crystal surface, which suppresses the electron flux to the sensor. These magnets were fixed to a grounded stand, and the distance between the magnets (19 mm) was chosen to minimize restriction on species reaching the QCM crystal. The body of the QCM was wrapped with Kapton tape to isolate it from the ground. Note that the diameter of the opening directly in front of the crystal was 8 mm. A DC bias power supply (HCS-3104, Manson) was connected to the chassis of the QCM to enable repulsion of ions by a positive bias voltage. A resistor (16 Ω) is added in series with the power supply to protect it from high currents, and a capacitor (470 μF) is placed in parallel to stabilize the bias voltage when high current is drawn from the plasma.

When the DC bias voltage is set to 0 V, the total deposition rate R_t , including Ti atoms and ions, is measured by the QCM. Then, a positive bias of 25 V is set to repel positive ions, enabling selective measurement of neutral Ti deposition rate, R_n . The ion contribution to the deposition rate, R_i , is then determined as

$$R_i = R_t - R_n. \quad (2)$$

In situ mass- and energy-resolved ion flux measurements were carried out using a mass spectrometer (EQP300, Hiden Analytical). The detected ionic species include $^{36}\text{Ar}^+$, $^{50}\text{Ti}^+$, $^{40}\text{Ar}^{2+}$, and $^{48}\text{Ti}^{2+}$. Due to saturation of the secondary electron multiplier (SEM) detector when measuring the more abundant isotopes ($^{40}\text{Ar}^+$ and $^{48}\text{Ti}^+$), the less abundant isotopes $^{36}\text{Ar}^+$ and $^{50}\text{Ti}^+$ were used to represent singly-charged argon and titanium ions, respectively. All recorded counts were subsequently corrected using the corresponding natural isotopic abundance factors. Energy distribution functions were integrated over the energy range 0–20 eV to determine the total ion fluxes reaching the detector. The mass spectrometer head was lifted to allow space for connecting either the passive thermal probe or the QCM ion meter. During mass spectrometry measurements, the probes were removed, and the spectrometer head was lowered so that its orifice aligned with the same position as the probes, 100 mm from the target centre.

3. Results

3.1. Typical waveforms for pulse configurations

Figure 2 presents the temporal evolution of target voltage, target current, and discharge power for a standard HiPIMS discharge and several chopped HiPIMS configurations under the weaker unbalanced magnetic field configuration (C5E5).

In the standard HiPIMS configuration, the voltage waveform is nearly rectangular, showing a small drop after plasma ignition before stabilizing. The corresponding current waveform exhibits an increase with a little delay caused by the time required to initiate the discharge from a low initial density of residual seed electrons [6, 16, 17], before reaching a steady plateau that reflects sustained plasma conditions.

In the 5(30, 20, 10) configuration, the first micropulse exhibits an initial delay in current onset and reaches a lower peak current compared to the second and third segments. This behavior is commonly observed and is attributed to the relatively low density of residual charge carriers, such as electrons, argon ions, and metal ions, present at the start of the pulse sequence [6, 9, 10]. In contrast, the second and third micropulses show a steeper current rise and higher peak values, resulting from the presence of residual charge carriers that remain in the near-cathode region during the brief 10 μs delays. These short intervals preserve ion and electron populations, allowing for faster discharge ignition and higher current. As the sequence progresses, cumulative effects such as gas heating and sputtering wind lead to a depletion of

the working gas near the target (gas rarefaction), reducing the ionization probability and, consequently, the discharge current [6, 9, 18].

In the second chopped HiPIMS configuration, 5(30, 20, 40), the pulse sequence is similar to the previous configuration, but with a longer 40 μs delay between pulses. As in the earlier case, the first micropulse exhibits a delayed current onset; however, its peak current is comparable to that of the second micropulse and higher than for the 5(30, 20, 10) case, which can be explained by the slightly higher voltage necessary to sustain the same pulse power. The subsequent pulses continue to exhibit faster current rise rates due to residual charge carriers remaining from prior discharges. Despite this, the overall peak currents in the later pulses are slightly reduced and eventually stabilize, indicating a steady-state discharge condition under the extended off-time.

In the final chopped HiPIMS configuration, 5(50, 20, 40), the first micropulse is longer (50 μs) than in previous modes and exhibits a markedly higher peak current compared to both the subsequent pulses in the same sequence and the pulses observed in earlier configurations. The elevated peak is attributed to the extended length of the first pulse, which allows the discharge to fully evolve. The following 20 μs micropulses, although characterized by a faster current rise due to residual charge carriers, do not reach the same peak current as the initial pulse. The peak current progressively decreases across the later pulses until stabilizing (in the last two pulses). This decrease is influenced not only by reduced charge carrier availability and possible gas rarefaction, but also by power balancing, since the pulse power and average power are fixed, the high initial peak results in a high power input early in the sequence, limiting the allowable power, and thus the peak current, of the later segments to remain within the system's average power constraints.

3.2. Effect of the magnetic field

Figure 3 shows the energy flux, the deposition rate, and Ti and Ar ion fluxes to the substrate, measured by the thermal probe at a floating potential, the QCM ion meter, and the mass spectrometer, respectively, positioned 100 mm from the target, using various pulse modes and magnetic field configurations. The comparison includes standard HiPIMS with a 130 μs negative pulse and chopped HiPIMS, which maintains the same total negative pulse length but employs a 5(50, 20, 40) pulse sequence. The energy flux is normalized to the 130 μs standard HiPIMS mode under the C5E5 magnetic field configuration.

As illustrated in Figure 3a, the results clearly demonstrate that both the pulse shape and magnetic

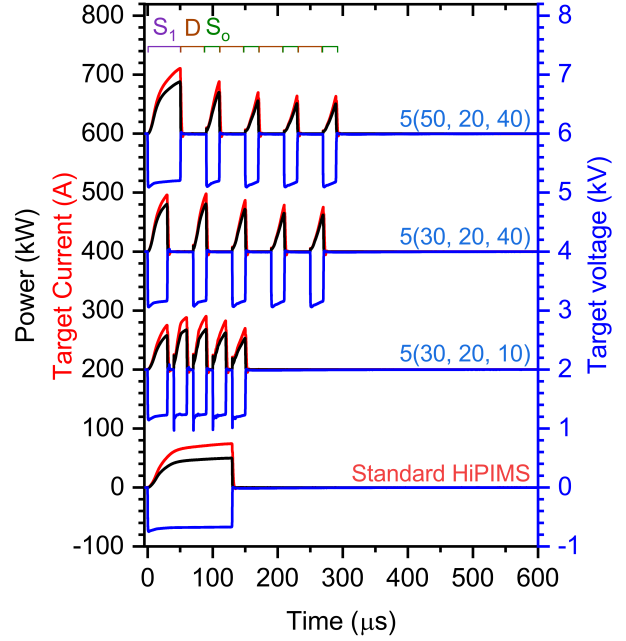


Figure 2. Selected waveforms of the target voltage, the target current, and the power for standard HiPIMS and various chopped HiPIMS pulse configurations (5(S_1 , S_0 , D)). The average power and pulse power were kept the same across all conditions.

field configuration have a significant impact on the energy delivered to the substrate. Chopping the HiPIMS pulse consistently increases the energy flux to the substrate relative to standard HiPIMS for all magnetic field configurations.

Reducing the magnetic imbalance from the highly unbalanced, C0E0, configuration to the moderately unbalanced, C0E5, configuration has minimal influence on the energy flux for either pulse mode; the values remain virtually identical. In contrast, further balancing the field, C0E10, lowers the energy flux for both standard and chopped HiPIMS. Conversely, introducing a weaker unbalanced configuration, C5E5, than C0E0, produces a pronounced increase in energy flux for both pulse configurations.

Figure 3b presents the deposition rate, which is broken down into Ti neutral, ion, and total components, highlighting the distinct contributions of each species to film growth. For all magnetic configurations, the chopped HiPIMS pulse mode consistently yields higher total deposition rates compared to standard HiPIMS. This enhancement is primarily attributed to an increase in the ion flux, while the neutral contribution is only slightly increased.

A progressive increase in deposition rates is observed as the magnetic field configuration becomes more balanced, transitioning from C0E0 to C0E5 and subsequently to C0E10, for both standard HiPIMS and

chopped HiPIMS pulse modes separately. Both ion and neutral deposition rates show a clear and consistent increase. Moving to the C5E5 configuration, which remains unbalanced, but with a weaker magnetic field than in C0E0, a substantial increase in total deposition rate is evident for both pulse modes compared to C0E0. This configuration appears to facilitate ion transport to the substrate, as reflected in the significantly higher ion contribution.

The standard HiPIMS shows a slightly lower deposition rate for the more balanced magnetic field configuration, C0E10, compared to C5E5, while the chopped HiPIMS regime exhibits identical deposition rates. Moreover, in the C5E5 configuration compared to C0E10, the contribution of ions increases at the expense of neutrals in both pulse modes.

According to Figure 3c, the mass spectrometry results indicate a higher flux of both Ti^+ and Ar^+ ion species in the chopped HiPIMS compared to the standard HiPIMS, for all magnetic field configurations. This increase is primarily dominated by Ar^+ ions. Additionally, the fluxes of doubly ionized species Ar^{2+} and Ti^{2+} are also higher in the chopped HiPIMS mode.

For Ti^+ ions, there is minimal variation from C0E0 to C0E5; however, a slight decrease is observed at C0E10 for both standard and chopped HiPIMS. In contrast, the Ar^+ ion intensity decreases more significantly as the magnetic field changes from C0E0 to C0E5 and then to C0E10, for both the standard and the chopped HiPIMS. When the magnetic field is changed from C0E0 to C5E5, both Ti^+ and Ar^+ ion intensities decrease, with the reduction being more significant for Ar^+ ions for both standard and chopped HiPIMS. Compared to C5E5, C0E10 shows a slightly higher Ti^+ ion intensity for both standard and bipolar HiPIMS, while the Ar^+ ion intensity remains relatively unchanged.

Although all diagnostic tools were placed at the same distance from the target and operated under identical experimental conditions, they show some contradictory trends. For example, while the QCM ion meter shows an increase in Ti species for the more balanced magnetic field configurations, this trend is not exactly mirrored in the passive thermal probe data. In the case of the Ti^+ ion flux measured by the QCM ion meter and the mass spectrometer, discrepancies are also observed under identical conditions. Specifically, as the magnetic field becomes more balanced, the QCM ion meter data show a stronger Ti^+ ion contribution, while an opposite trend is reflected in the mass spectrometer results. Potential reasons behind these discrepancies are given in the Discussion section.

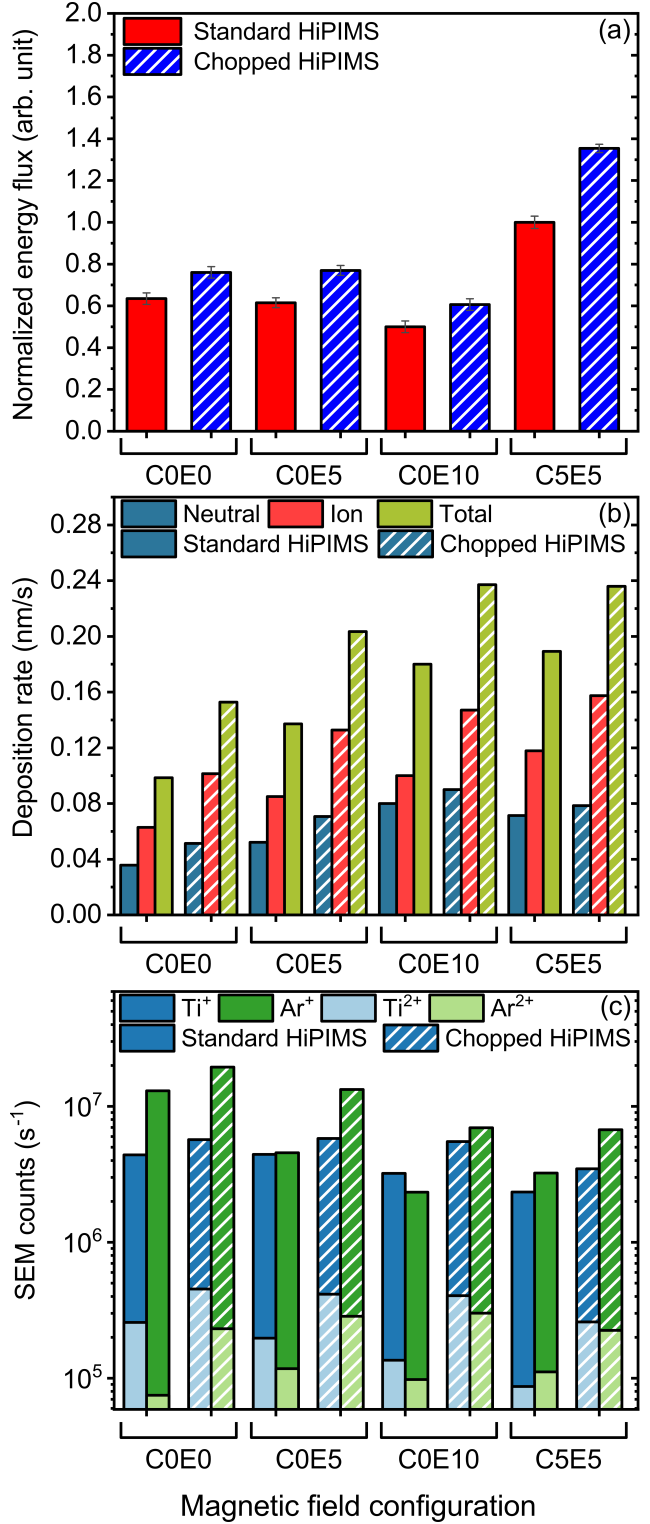


Figure 3. (a) Energy flux measured by the thermal probe at floating potential, (b) neutral Ti atoms, Ti ions, and total deposition rates obtained from the QCM ion meter, and (c) integrated ion energy flux distribution functions over the energy range 0–20 eV measured by MS, for various pulse modes, standard (130 μs) and chopped HiPIMS 5(50, 20, 40) under different magnetic field configurations. The average power and pulse power were kept the same for all conditions.

3.3. Effect of the pulse length in chopped HiPIMS

Figure 4 shows the effect of the pulse length on the energy flux, the deposition rate, and Ti and Ar ion fluxes reaching the substrate at a distance of 100 mm from the target center under the C5E5 magnetic field. The lengths of the first, S_1 , and the other pulses, S_o , were increased incrementally by 10 μs at each step, while the delay time was held constant at 10 μs . Let us remind that the frequency was changed to maintain the same pulse and average power. The energy flux is normalized to the 5(80, 70, 10) pulse configuration.

As shown in 4a, when the pulse lengths increase from 5(30, 20, 10) μs to 5(50, 40, 10) μs , the energy flux gradually decrease. Beyond this point, further increases in pulse lengths up to 5(80, 70, 10) μs result in constant energy flux values.

Furthermore, as shown in Figure 4b, the deposition rates of Ti atoms and ions exhibit a trend consistent with the energy flux measurements (Fig. 4a), wherein longer pulse lengths are associated with slightly reduced deposition rates, but the values saturate for long pulse lengths. This reduction is primarily attributed to a decrease in the Ti ion contribution, while the Ti atom contribution remained relatively stable throughout the entire range of pulse durations, exhibiting only a minor decline.

The mass spectrometer results also revealed a decrease in the intensity of both singly and doubly ionized species as the pulse length increased from 5(30, 20, 10) to 5(60, 50, 10), after which the ion signals remained constant, see Figure 4c. Notably, the difference in signal intensity between Ti^{2+} and Ar^{2+} became more pronounced with longer pulse segments.

3.4. Effect of the delay time in chopped HiPIMS

Figure 5 illustrates the effect of the delay time between individual pulses of the chopped HiPIMS configurations on the energy flux, the deposition rate, and Ti and Ar ion fluxes at the substrate for the C5E5 magnetic field configuration. For the chopped HiPIMS, the pulse configuration 5(50, 20, D) was used, where only the delay time (D) between micropulses was varied in 10 μs increments, starting from 10 μs . The delay of 0 μs corresponds to the standard HiPIMS. In all cases, the total length of the negative pulses was fixed at 130 μs . The energy flux is normalized to the standard HiPIMS case.

Overall, chopped HiPIMS exhibits a higher energy flux compared to standard HiPIMS (Fig. 5a). In the chopped mode, the lowest energy flux is observed at the shortest delay time (10 μs). As the delay time increases, the energy flux initially increases and then remains approximately constant.

Figure 5b shows that the total deposition rate

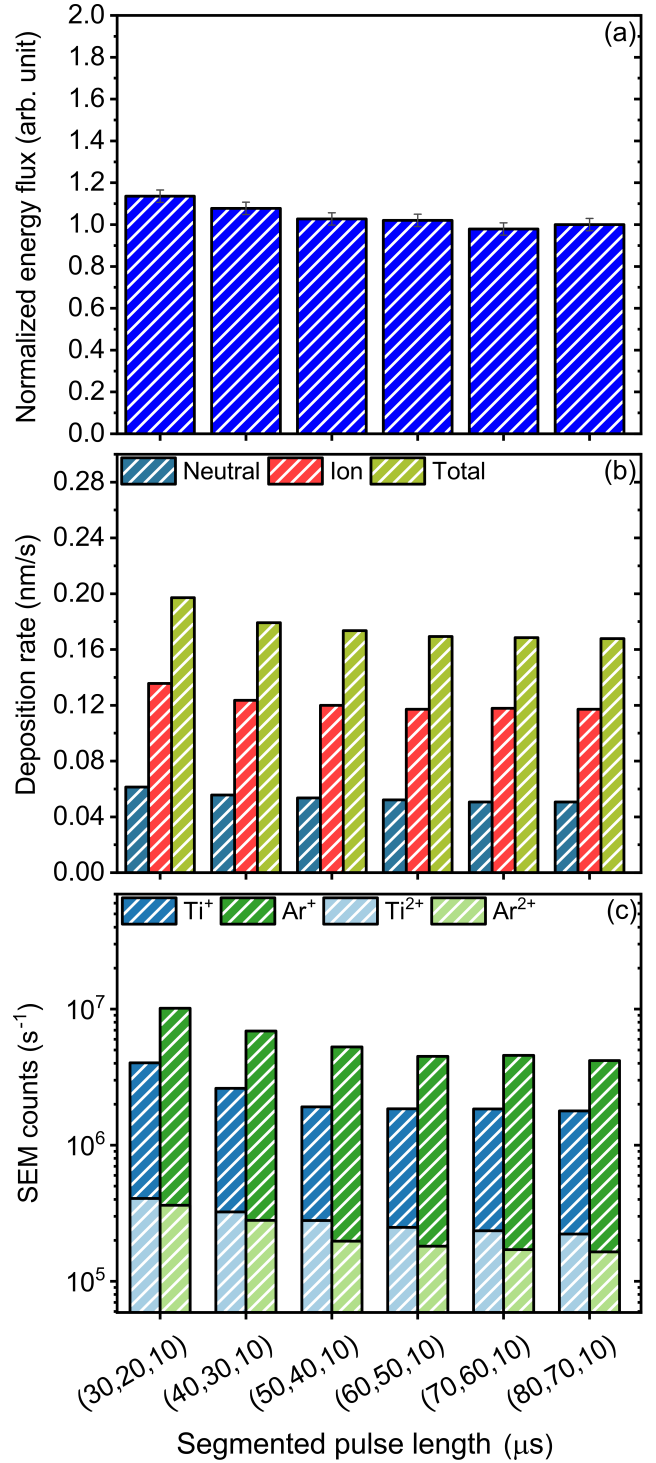


Figure 4. (a) Energy flux measured by the thermal probe at floating potential, (b) neutral Ti atom, Ti ion, and total deposition rates measured by the QCM ion meter, and (c) integrated ion energy flux distribution functions over the energy range 0–20 eV measured by MS, for various chopped HiPIMS pulse configurations. The first and other pulse lengths (S_1 , S_o) were increased by 10 μs in each step. The average power and pulse power were kept the same for all conditions.

gradually increases with increasing delay time and that this is mainly due to the increasing flux of Ti ions, while the Ti atom deposition rate remains nearly constant. This supports the increase in the energy flux shown in Figure 5a. On the other hand, the total deposition rate increases without reaching a saturation point in the range of conditions investigated.

As shown in Figure 5c from the mass spectrometer data, standard HiPIMS exhibits lower ion intensities, particularly for Ar^+ and doubly ionized species. When the HiPIMS pulse is chopped, increasing the delay leads to a general rise in ion intensities, with the increase being more pronounced for Ar ions.

3.5. Effect of the pulse length in standard HiPIMS

The previous section described the effect of the pulse delay in the chopped HiPIMS mode. If the pulse delay in the five-segment chopped HiPIMS is increased even more (beyond the range presented in the previous section), it will converge on a regime similar to standard HiPIMS with 5 times shorter pulse length and 5 times higher frequency. To facilitate a meaningful discussion on the benefits of chopped HiPIMS, we also investigated standard HiPIMS discharges with varying pulse lengths and repetition frequencies, while maintaining average and pulse power constant. For the reference pulse length of 130 μs , the repetition frequency was 96 Hz. For other pulse lengths, t_{on} , the repetition frequency scales as $\propto 1/t_{\text{on}}$.

Figure 6 presents the effects of these variations on energy flux, deposition rate, and the fluxes of Ti and Ar ions at the substrate, measured under the C5E5 magnetic field configuration. The energy flux is normalized to the 130 μs standard HiPIMS configuration.

The thermal probe measurements, as shown in Figure 6a, reveal a pronounced decrease in energy flux as the pulse length increases from 20 to 100 μs . This initial drop is followed by a continued, but considerably slower, decline extending to the 200 μs pulse length.

A comparable trend is observed in the QCM ion meter data (Figure 6b). The deposition rate decreases sharply within 20 to 100 μs , after which the reduction becomes more gradual, but with distinct behavior between different species. The Ti ions show a more pronounced decline from 20 to 100 μs , whereas the Ti atom flux remains nearly constant between 20 and 50 μs before experiencing a noticeable drop by 100 μs . Beyond this point, the decrease in both Ti atoms and ions continues at a much slower rate, extending up to 200 μs .

The mass spectrometer results also follow this general pattern (Figure 6c). Ion flux decreases substantially between 20 and 100 μs , then continues to decline more slowly up to 200 μs . The intensity

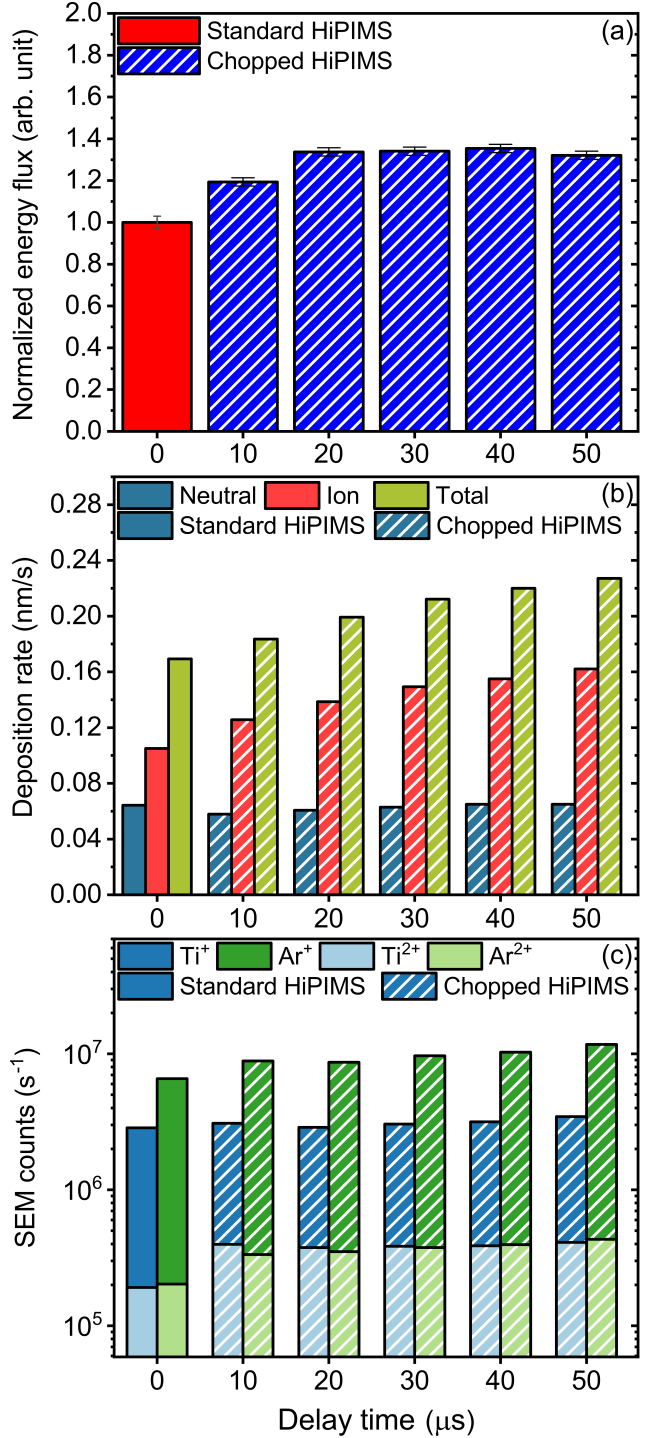


Figure 5. (a) Energy flux measured by the thermal probe at floating potential, (b) neutral Ti atom, Ti ion, and total deposition rates obtained from the QCM ion meter, and (c) integrated ion energy flux distribution functions over the energy range 0–20 eV measured by MS, for various pulse configurations, standard (130 μs) and chopped HiPIMS 5(50, 20, D). The delay time between segments (D) was increased by 10 μs in each step. The average power and pulse power were kept the same for all conditions.

difference between both singly and doubly ionized Ar and Ti is more pronounced between 20 and 50 μs , in favor of the Ar species, but gradually diminishes beyond 50 μs . This indicates that the Ar^+/Ti^+ ratio is higher for shorter pulses.

4. Discussion

The improved performance with shorter pulse lengths is rooted in several mechanisms that determine the transport of species to the substrate. The key factors are the ionization of the sputtered target material atoms and their return back to the target. Many of the phenomena discussed below inherently change the ionization or ion return probability, which then affect the deposition rate or the ionized flux fraction as described qualitatively by the pathway models, for example, by Vlček and Burcalová [19].

At the start of a pulse, sputtering is efficiently driven by process gas ions. However, as the pulse continues, the proportion of ionized sputtered target species increases, and these ions are drawn back to the negatively biased target surface. This ion back-attraction initiates a self-sputtering regime [20–22]. While self-sputtering can, for specific materials, sustain the plasma without process gas ions, it typically results in a lower deposition rate compared to sputtering driven by process gas ions [23]. Consequently, longer pulse durations can reduce deposition efficiency by decreasing the net flux of sputtered material reaching the substrate [9, 12, 24]. However, it should be noted that the effectiveness of self-sputtering is material-dependent [5, 25, 26]. In the case of titanium, the self-sputtering yield is only slightly lower than that of argon-ion sputtering [5]. Therefore, in this specific context, the impact of reduced sputtering yield during self-sputtering is expected to be minimal, although the deposition rate still decreases due to the back-attraction of Ti ions to the target.

Additionally, gas rarefaction occurs during long pulses due to continuous Ar ionization and the momentum transfer from energetic sputtered atoms, which displace Ar atoms away from the target, a phenomenon often referred to as “sputtering wind” [27, 28]. This local depletion of working gas limits further Ar^+ production and reinforces dependence on the possibly less efficient self-sputtering process, especially for materials with lower sputtering yields than the process gas ion.

Moreover, the spatial dynamics of ion transport contribute to material loss, particularly through radial diffusion [29, 30]. In HiPIMS, acceleration of ions tangentially outward from the racetrack and the associated increased radial material loss have been

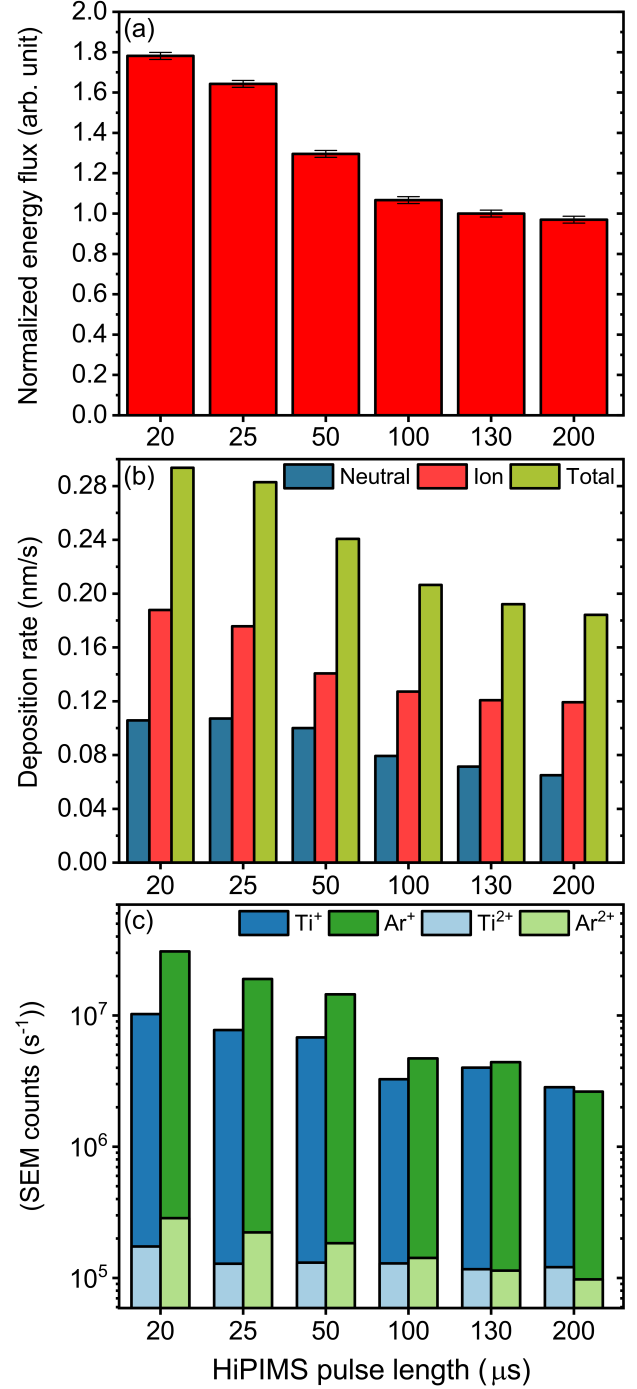


Figure 6. Energy flux measured by the thermal probe at floating potential, (b) neutral Ti atom, Ti ion, and total deposition rates obtained from the QCM ion meter, and (c) integrated ion energy flux distribution functions over the energy range 0–20 eV measured by MS, for HiPIMS discharges with varying pulse lengths and repetition frequencies at constant average and pulse power. The average power and pulse power were kept the same for all conditions.

reported [30, 31]. This was explained by azimuthal electric field oscillations associated with the rotating ionization zones (called spokes) [32, 33]. Although not exclusively dependent on pulse length, longer pulses provide greater temporal windows for such radial transport mechanisms to develop. The significance of this radial loss is underscored by studies aimed at its mitigation. I.-L. Velicu et al. [34] showed that adding an external magnetic field can limit the radial ion losses, increase deposition rate, ionized flux fraction, and ion energy for a tungsten target.

Generally, by mitigating ion back-attraction [11, 24, 35, 36], reducing gas rarefaction, and suppressing the onset of self-sputtering [8, 9, 11, 37, 38], a shorter pulse length promotes more efficient ion transport to the substrate. Shimizu et al. [39] reported that, at constant average power and peak current, the deposition rate increases with shorter pulse lengths, reaching a maximum at about 25–50 μ s. Similarly, Barker et al. [9] found that at a constant average power, chopped HiPIMS with four 25 μ s micropulses achieved a higher deposition rate than with two 50 μ s micropulses.

Having reviewed the key phenomena in HiPIMS discharges and the relevant literature, we now turn to the results of the present study. Before doing so, the possible sources of discrepancies between the different diagnostics when the magnetic field is varied (see Figure 3 in Section 3.2) should be considered. It should also be noted that, despite these potential discrepancies, the measurements in Figures 4, 5, and 6 are in very good agreement.

The specific characteristics of each diagnosis are highlighted here. The thermal probe responds to the total energy flux from all incoming species, including Ti and Ar atoms and ions, as well as electrons. Since the probe is at a floating potential, it is expected that ions contribute with a higher energy per arriving atom than neutral atoms. The QCM ion meter, in contrast, measures the absolute particle flux of film-forming species only, being sensitive to Ti atoms and ions while reflecting incoming Ar. A key advantage of the QCM ion meter and the thermal probe is their large acceptance area. They are not sensitive to the particle's angle of incidence (except for the geometrical shadowing effect in the case of the ion meter, caused by the presence of the shielding magnets). Finally, the mass spectrometer measures the particle flux of only charged species, but it discerns between Ar and Ti species and their charge states. However, the SEM counts cannot be easily converted to particle flux densities. Moreover, MS samples ions through a small orifice and within a limited acceptance angle, making it less sensitive to ions arriving from off-axis directions. The overall sensitivity depends on the ion energy

and species mass, and can vary with different plasma conditions. This becomes particularly important when comparing results for different magnetic field configurations, as the magnetic field can influence the spatial distribution of ions via ambipolar diffusion. Changes in the magnetic field can thus affect the detection efficiency of the mass spectrometer at various energies, while the QCM ion meter, with its larger exposure area, remains less affected.

When the magnetic field balance increases from C0E0 to C0E10, the QCM shows a significant rise in Ti atom and ion flux, while the mass spectrometer records a decrease in Ti^+ (and Ar^+). This can be caused by the mismatch between the QCM's broad angular acceptance versus the MS's narrow acceptance range. At the same time, the thermal probe shows only a slight decrease in energy flux, suggesting that despite increased Ti flux, the energy of arriving species is insignificant. In contrast, the significant increase in energy flux observed at C5E5 compared to C0E10 is not accompanied by a corresponding rise in Ti atom or ion flux in either the QCM ion meter or the mass spectrometer. The QCM shows only a slight increase in ion flux and a small decrease in neutrals compared to C0E10, which cannot account for the substantial energy enhancement. This discrepancy suggests that the additional energy is likely carried by species not effectively captured by either diagnostic, such as energetic Ar atoms or ions, to which the MS has reduced sensitivity, or electrons. It is worth noting that all these trends have been verified through repeated measurements using all three diagnostic techniques.

As observed in Section 3.2, the deposition rate increases as the magnetic field imbalance decreases from C0E0 to C0E10 and as the strength decreases from C0E0 to C5E5. This is in agreement with previous observations by Hajihoseini et al. [40]. Since the pulse power is kept the same in our study, we can assume that the ionization probability of sputtered species remains approximately constant for different magnetic fields, as shown by the same authors [40] under similar fixed-peak-current conditions. Therefore, the deposition rate trends can be explained by a reduced probability of back-attraction of Ti ions, allowing a larger fraction of ions to reach the substrate. This can be further understood by examining the role of the magnetic field in governing electron confinement within the ionization region above the racetrack. Mishra et al. [41] showed that reducing the magnetic field at the target weakens electron confinement, which in turn decreases the axial electric field within the magnetic trap region. This leads to a lower effective potential barrier, which normally restricts the escape of ionized sputtered species, resulting in a higher deposition rate

and ionized flux fraction. Their study showed that a 33% decrease in magnetic field strength resulted in up to a 40 V increase in plasma potential at 10 mm from the target during the initial phase of the pulse, and a 15 V rise at peak discharge current, significantly enhancing ion escape.

Having considered the influence of the magnetic field, where the C5E5 configuration was found to yield superior results, the remainder of the study was therefore conducted under this condition. The results from Figures 4 and 6 reveal that increasing the length of individual micropulses, while keeping the averaged power constant, leads to a gradual decrease in both deposition rate and energy flux, which, as mentioned before, can be explained by the increased effective ion return probability. The decrease in singly and doubly ionized Ar and Ti with increasing pulse length also supports the key role of the back-attraction effect (Figure 4c). A similar reduction in energy flux with increasing pulse length has been reported in other studies. Tiron et al. [38] reported that in reactive HiPIMS at constant average power, increasing pulse length from 4 to 16 μs reduces ion fluxes to the substrate, shifts the plasma from gas to metal self-sputtering, and decreases both deposition rate and metal ion flux.

In addition, our results demonstrate that the delay between chopped pulses is a critical parameter for maximizing both deposition rate and energy flux, with an optimal off-time of at least 30 μs (Fig. 5). The introduction of longer D serves two main purposes. First, it provides a sufficient window for sputtered metal ions to escape the near-target region and travel to the substrate, preventing them from being attracted back to the target upon reignition of the plasma. Second, the increased Ar^+ signal at longer delays indicates that this off-time allows for partial replenishment of the working gas. This creates more favourable conditions for the next micropulse, promoting efficient sputtering via Ar ion bombardment rather than relying on less effective self-sputtering. The results by Barker et al. [9] are consistent with our study, showing a high deposition rate for multiple short pulses with long off-times compared to standard HiPIMS in the same total negative pulse length. Hnilica et al. [6] observed a complex trend at constant average power and pulse power. They found that an optimal 50 μs delay maximized the Ti^+ ion density, while the shortest delay (20 μs) yielded the highest neutral density due to rarefaction and reduced collisions. In contrast, very long delays (150 μs) were detrimental, producing the lowest particle densities due to species loss to the chamber walls. In agreement, Antonin et al. [8] studied the delay for a tungsten target at constant average power with pre-ionization. They

found an optimal delay of 50 μs , which maximized the deposition rate, corresponding to peaks in both ion flux and neutral density. However, the authors likely did not maintain constant average pulse power, which can cause significant variations in the ionization degree and, consequently, complicate interpretation and comparison with the present study.

It is emphasized that both the average power and the pulse power were kept constant, ensuring a similar degree of ionization and a valid comparison between the evaluated pulsing strategies. Under these conditions, standard HiPIMS operated at higher frequencies demonstrated superior performance compared to the chopped HiPIMS mode. More specifically, standard HiPIMS with a 20 μs pulse length operated at the highest repetition frequency of 625 Hz (Figure 6) can be compared with the best-performing chopped configuration, 5(50, 20, 40) operated at 96 Hz (Figure 5). The standard HiPIMS exhibits 25 % higher energy flux, 25 % higher total deposition rate, and 20 % higher Ti ion flux. Significantly higher SEM ion counts are also observed for both Ti^+ and Ar^+ ions. However, it should be noted that the quantitative comparison of results from different series of experiments, which were not performed in close succession, may be subject to higher systematic errors due to changing plasma conditions (target erosion) and thermal probe capacitance (material deposited on the probe). A repeated measurement of standard HiPIMS with a 20 μs pulse length and the chopped 5(50, 20, 40) configuration, performed in a row, confirmed the higher energy flux for the standard HiPIMS case, but the difference was only 11 % (not shown).

The main distinction between chopped HiPIMS and standard HiPIMS at short pulse lengths and high frequencies lies in the delay time introduced between micropulses in the chopped mode. For instance, by progressively increasing the delay in the 5(50, 20, D) configuration, the system closely approximates the operating conditions of standard HiPIMS with a 20 μs pulse length at a five times higher frequency. We have verified that the length of the first micropulse does not play a crucial role, as the difference in energy flux between the 5(50,20,40) and a 5(20,20,40) configuration is insignificant (not shown). The sufficient off-time in standard HiPIMS (1580 μs) allows near-complete refilling of Ar near the target and effective suppression of gas rarefaction, compared to the shorter off-time in chopped HiPIMS. Lundin et al. [42] showed that a complete Ar refill requires long off-times on the order of a few ms, judged by the dependence of peak current on pulse-off time. In agreement with that, Kozák [43] calculated that a complete refill requires around 1 ms. We can conclude that the consistent application of short-duration pulses

and sufficient off-time are key factors in achieving high ion fluxes at constant pulse and average power.

5. Conclusions

Chopped HiPIMS was systematically investigated under constant average and pulse power to elucidate its effect on the deposition rate, ionized flux fraction, and the energy delivered to the substrate, which are the main parameters that strongly influence film growth. The study combined the results of total energy flux, titanium neutral and ion deposition rates, and ion counts from the mass spectrometer to provide a detailed understanding of the deposition conditions. Except for the case when the magnetic field configuration was varied, all complementary measurements were in very good agreement.

It was shown that chopped HiPIMS generally improved energy flux and deposition rates compared to standard HiPIMS with the same total negative pulse length. A weaker, unbalanced magnetic field configuration was proven effective in reducing ion back-attraction and, consequently, maximizing particle and energy fluxes to the substrate. Among chopped HiPIMS configurations, longer individual micropulses decreased deposition rates and energy flux. On the other hand, increasing the delay time between micropulses significantly enhanced these parameters, with an optimal off-time of at least 30 μs .

Finally, chopped HiPIMS configurations were compared to standard HiPIMS operated at higher frequencies with consistently short pulse lengths. The standard HiPIMS regime with a short pulse of 20 μs yielded higher energy fluxes, deposition rate, and Ti^+ and Ar^+ ion fluxes than a comparable chopped HiPIMS configuration. We conclude that short pulses enable the release of target material ions from the vicinity of the target, effectively reducing ion back-attraction, as previously reported in the literature. Sufficiently long off-times between pulses enable working gas replenishment and mitigate gas rarefaction.

In summary, while chopped HiPIMS provides notable benefits, our findings emphasize that the consistent application of short pulse length, together with adequate off-times, is the key factor for maximizing ion fluxes, energy fluxes, and deposition rates. These findings highlight the context-dependent nature of pulse optimization and suggest that a carefully tuned standard HiPIMS process can be sufficient to obtain optimal deposition conditions.

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