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# HIPIMS
# NEW POSSIBILITIES FOR INDUSTRY

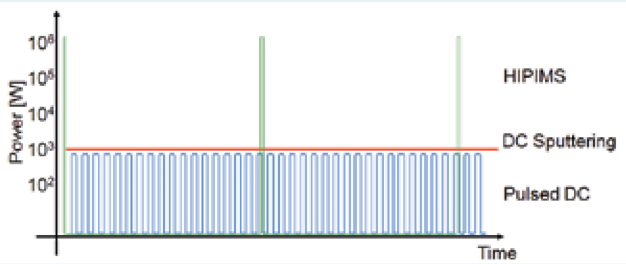


**Figure 1: Schematic representation of the HIPIMS technology compared to DC and Pulsed-DC sputtering. In HIPIMS the same average power is delivered in short pulses with pulse power exceeding $10^4$ W/cm$^2$.**

**Figure 2: The new generation of TruPlasma Highpulse power supply**

## Background

High Power Impulse Magnetron Sputtering (HIPIMS) is the youngest Physical Vapor Deposition (PVD) technique available to the industry. Figure 1 explains schematically the meaning of the name HIPIMS: in DC sputtering a continuous power is applied to the cathode and in the case of Pulsed DC the output current and voltage are turned off for a given period of time which is normally short enough to result in a duty cycle not less than 50%. In contrary, in HIPIMS the voltage and current are delivered in short pulses with duty cycle of 1 to 10 %. Thus, to obtain the same average power as in DC or Pulsed DC sputtering power delivered in one pulse can exceed $10^4$ W/cm$^2$ (normalized by whole area of the cathode) and the current reaches several A/cm$^2$. The pulses of high power and current produce plasma discharge with electron density up to $10^{18}$ m$^{-3}$ where the fraction of ionized metal vapor can exceed 90% [1, 2]. Such a high ionization of sputtered metal vapor was shown to have significant influence on the morphology and properties of the coating which includes preferential orientation, coating densification, higher hardness or improved adhesion [2, 3, 4].

One of the common way to generate ionized vapor on industrial scale is the cathodic arc deposition. Despite high ionization degree and high deposition rates arc deposition suffer from the presence of macroparticles, i.e. microscopic hot cathode debris particles or droplets which decrease the quality of the coating [5]. Therefore, HIPIMS sputtering is an ideal alternative which provides high ionization of metal vapor and advanced arc management functionality of power supply for an effective elimination of arcing and macroparticles.

We have introduced the first HIPIMS power supply available commercially on the market in 2003. For more than one decade the first generation of TruPlasma Highpulse known as Huettinger HMP was successfully applied for deposition of anti-wear and protective coatings, metallization of trenches with high aspect ratio or deposition of transparent insulating as well as conductive oxides [3, 6, 7], to name just few examples. The newest generation of the TruPlasma Highpulse power supplies (Figure 2) offers versatile arc management, unique control of voltage and current peak shape as well as the average power delivery control enabling HIPIMS industrialization in various applications.

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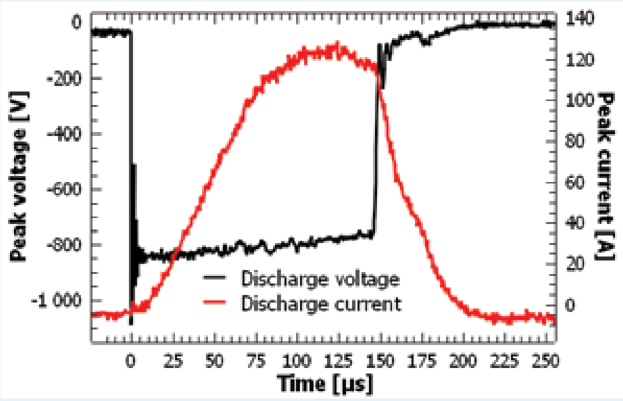


**Figure 3: Example of voltage and current pulse shape typical for previous air-cooled TruPlasma Highpulse power supply generation.**

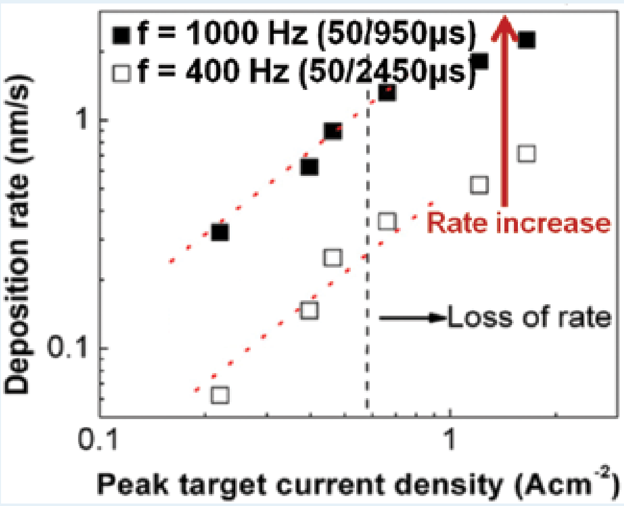


**Figure 4: Dependence of the deposition rate on the peak current density for two pulse time/frequency configurations [9]. Horizontal arrow marks the current density onset of the deposition rate decrease. Vertical arrow shows the possibility of the deposition rate increase at constant peak current density and increased HIPIMS pulsing frequency.**

## The challenge: Making HIPIMS ready for industrial application

There are two main concerns related to the HIPIMS application on industrial scale: i) the limitation of the power supply capacitor bank in maintaining constant voltage and current throughout the whole HIPIMS pulse and ii) lower deposition rate compared to the DC magnetron sputtering with the same average power [2].

Since its introduction HIPIMS technology is often based on a capacitor bank in which a thyristor switch is used to periodically release stored energy to the load in pulses. This allows to reach few kiloamperes and kilovolts in pulse, however, the exact shape of the current and voltage depend on the size of the capacitor bank and on whether the circuit inductance or the plasma resistance limits the current. If the circuit inductance is low both voltage and current can increase within few µs to a sharp peak. It is followed by a saturation of the voltage to a level determined by the plasma discharge. However, as the energy is released from the capacitor bank the output voltage decreases to level at which the discharge cannot be sustained. As a result current also decreases and the plasma discharge turns off [2]. In addition, the actual shape of the HIPIMS shape depends also on the gas type and its pressure as well as the magnetron design and size. Therefore, in the purest form of HIPIMS pulses where no pre-pulse or underlying low-power DC is used, the current onset is delayed respect to voltage as depicted in Figure 3 [8].

Second challenge of HIPIMS industrialization is the deposition rate. Several effects have been proposed to be the reason for reported lower deposition rate including (i) ionized metal vapor lost (back-attraction) due to self-sputtering (ii) effect of a reduced sputtering yield typically lower for metal ions compared to argon ions (iii) ion loss due to an azimuthal transport across the magnetic field lines [2]. Furthermore, Alami et al. showed that the deposition rate changes as a function of the peak current, and falls below the values obtained for DC at a certain current density as shown in Figure 4 [9]. The influence of the peak current on the reduction of HIPIMS deposition rate was recently confirmed for several metallic targets [10].

Indeed, a closer look to Figure 4 provides two important information: (i) a deposition rate declines as soon as a certain peak current density is reached, but (ii) for a fix current density the increase in the HIPIMS pulsing frequency shall result in an increase of the deposition rate. The latter, however, requires a precise control of the HIPIMS output voltage and current to provide repeatable pulses with elevated frequency and to maintain a constant peak voltage and current in pulses with duration up to 3 ms.

To solve both challenges TRUMPF Huettinger has recently introduced new generation of TruPlasma Highpulse power supplies. The application of controlled current pulse shape and average power regulation modes available on the market only in TRUMPF Huettinger HIPIMS units will be demonstrated in this paper with examples for metallic and reactive processes.

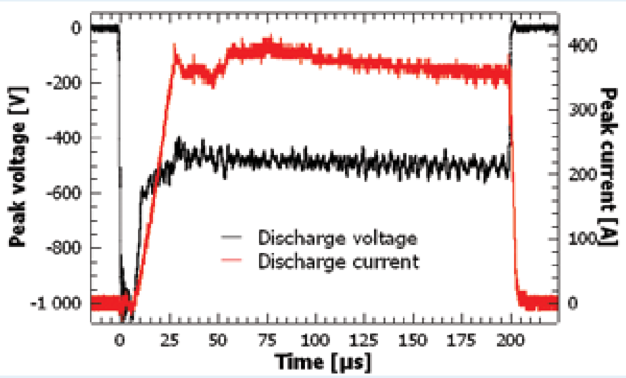


**Figure 5: Voltage and current pulse shape measured with the new HIPIMS power supply generation (TruPlasma Highpulse 4001 G2).**

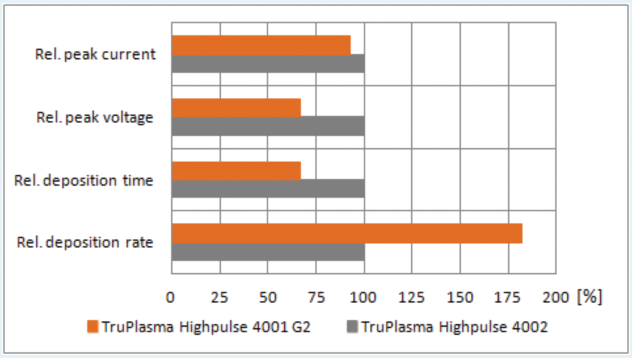


**Figure 6: Comparison of process parameters obtained by using two generations of HIPIMS power supply: air-cooled TruPlasma Highpulse 4001 and TruPlasma Highpulse 4001 G2.**

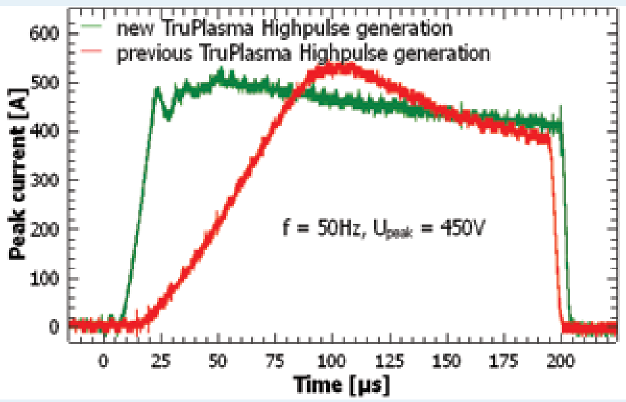


**Figure 7: Comparison of the pulse shape geometry available in previous (G1, air-cooled) and new (G2, water-cooled) TruPlasma Highpulse power supply generation.**

## The Solution: Control of HIPIMS pulse shape

In contrast to previous generation of HIPIMS power supplies, new generation is fully water-cooled. Therefore, the previous generation of TruPlasma Highpulse will be also referred as air-cooled or G1 and the new one as water-cooled or G2. An example of a controlled shape of voltage and current pulse waveform of the new water-cooled TruPlasma Highpulse are depicted in Figure 5. The shape of the voltage and current pulse can be kept stable over the whole pulse length and the onset of the current immediately follows the voltage. This is a remarkable change of the current pulse shape compared to air-cooled G1 HIPIMS generation depicted in Figure 3 where current rises slowly to reach its maximum almost at the end of the voltage pulse duration. In the new HIPIMS generation current reaches peak value in several µs and it is regulated to keep constant during the whole pulse duration. Such controlled stability of the HIPIMS current pulse is available on industrial scale only with the new generation of TruPlasma Highpulse 4000 power supplies.

The advantage of the controlled HIPIMS voltage and current pulse shape can be showed using the results of $TiO_2$ deposition by two generations of TruPlasma Hipulse power supply. For the $TiO_2$ deposition the same pulse length and frequency settings were used at two power supplies. Important process parameters are compared in Figure 6 in relative values where as a reference the values obtained with air-cooled TruPlasma Highpulse 4002 were used. The difference between measured peak current is less than 5% and a higher peak voltage in the case of G1 power supply can be a result of capacitor bank discharging during the pulse. Despite these small differences the most important finding is the influence of the controlled voltage and current pulse shape on the deposition rate: deposition rate obtained with the new water-cooled HIPIMS is almost two times higher compared to the value obtained with previous generation of HIPIMS power supplies (see Figure 6). Considering only the geometry of the pulses compared in Figure 7 it is clear, that the controlled voltage and current pulse shape provide higher power per pulse. Taking the peak power as:

$$P = \frac{1}{PT}\int_0^{PT} u(t)i(t)dt$$

where PT is the actual pulse time, the peak power estimated for two exemplary waveforms depicted in Figure 7 are $P_{G1}$ = 160 kW for G1 HIPIMS unit and $P_{G2}$ = 200 kW for TruPlasma Highpulse 4000 G2 with controlled voltage and current pulse shape. Thus, for HIPIMS pulses with equal pulse time, delivered with equal repetition frequency the same average power is delivered faster by the new generation of TruPlasma Highpulse units. This in turn has two further consequences: a remarkable decrease of the deposition time as shown in Figure 6 and an influence on the film morphology. A controlled shape of current pulse in G2 unit resulted in formation of $TiO_2$ film in almost pure anatase phase which was essential in this particular

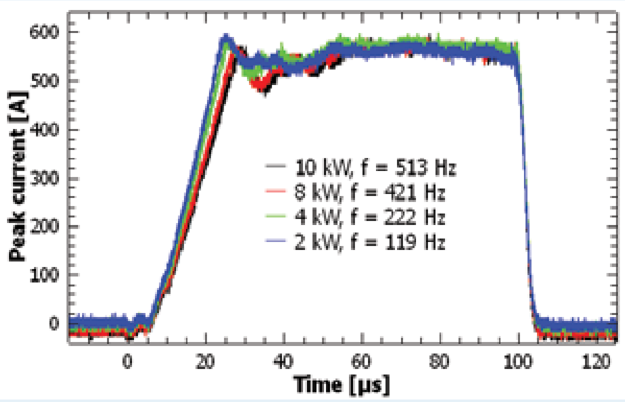


**Figure 8: HIPIMS current pulse waveforms of new generation of TruPlasma Highpulse unit operated in the average power controlled mode with fixed Pulse Time of 200 µs and different pulsing frequency for average power adjustment.**

application. Detailed experiments are carried on to confirm the $TiO_2$ phase transition to originate from a modified neutral-to-ion density ratio and plasma dynamics due to the stable current throughout the whole HIPIMS pulse time.

## Average power under control

The possibility to maintain a constant current and voltage during the whole HIPIMS pulse is also beneficial for HIPIMS sputtering in reactive processes. Nitride or oxide coatings deposited by HIPIMS has been shown to have superior structural, mechanical and optical properties [3, 4]. Since deposition rate typically depends linearly on the average power a combination of two HIPIMS parameters: peak current and duty cycle can be used to control process conditions by average power. The peak current has strongest influence on the film properties, thus a first step in HIPIMS processing is to define the appropriate peak current and voltage for best coating parameters. In the air-cooled generation of HIPIMS power supplies the average power would be adjusted manually taking into account the limitations of the capacitor bank and electrical parameters of the system. New generation of TruPlasma Highpulse power supplies was equipped with an average power regulation mode - an unique functionality available only in the TRUMPF Huettinger HIPIMS power supplies. Figure 8 depicts HIPIMS current and voltage pulses recorded with TruPlasma Highpulse 4002 G2 operated in the average power regulation mode on Ti target in argon atmosphere. The peak current (400 A), peak voltage (560 V) as well as the pulse length (100 µs) were set to be constant. As the average power was changed between 1 to 10 kW by the operator, its adjustment was done by an automatic change of the pulsing frequency to keep the set values unchanged. Thanks to an advanced current pulse shape regulation automatic change of the pulsing frequency by a factor of 10 does not have any influence on the current or voltage waveform (Figure 8). Alternatively, the frequency can be fixed at any value between 1 to 10000 Hz (or higher on request) and the average power will be regulated by an automatic change of the pulse length. Therefore, the use of new generation of TruPlasma Highpulse power supplies enables regulation of the average power to modify deposition time similar to DC and Pulsed-DC sputtering.

In the early investigation of HIPIMS discharge it has also been shown that the deposition rate can be higher if short HIPIMS pulses (<10 µs) are used [11]. Since in these conditions there is not enough time for metal to be ionized and back-attracted to the cathode the deposition rate is high [2]. To benefit from the expected enhancement of sputtering rate with short HIPIMS pulses, the pulse shape management available in TruPlasma Highpulse G2 seems to be essential. Therefore, the new generation of TruPlasma Highpulse allows the operation with pulse time from only few microseconds up to pulses of 3000 µs duration.

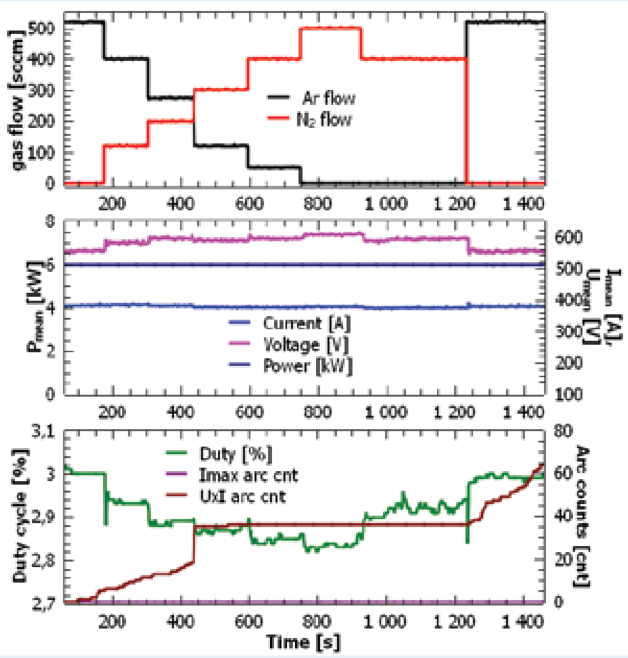


**Figure 9: Reactive process operated by TruPlasma Highpulse 4001 G2 in the average power control mode with fixed Pulse Time of 200 µs at different Ar/$N_2$ gas ratio.**

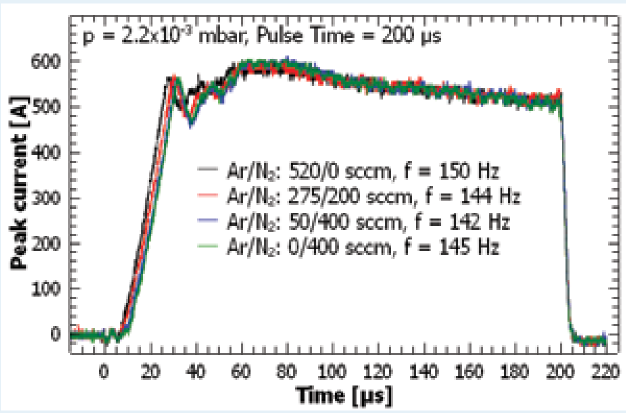


**Figure 10: Current pulse waveforms of the new generation TruPlasma Highpulse unit operated in the average power control mode with fixed Pulse Time of 200 µs at different Ar/$N_2$ gas ratio. The frequency was adjusted automatically by control algorithm as a response to changed Ar/$N_2$ gas ratio.**

## Stability in reactive processes

The most challenging processes are those utilizing reactive gases such as nitrogen, oxygen or methane. With the introduction of the reactive gas the discharge parameters and target condition change due to several factors: different ionization cross section of gases, different sputtering yield of gases, target poisoning, different secondary electron emission yield on clean and poisoned target surface, to name only few. Change of nitrogen concentration in $N_2$/Ar mixture have been studied for example by *Hala et al*. using a Cr target and air-cooled generation of TruPlasma Highpulse power supply [12]. For nominal pulses of 200 µs authors showed a change of the peak current value and an increase of current pulse onset delay with the increase of $N_2$/Ar ratio. Furthermore, at increased $N_2$ concentration higher peak currents were measured, followed by a steeper decrease of the current as the pulse develops as a direct consequence of a faster reduction of the charge stored in the capacitor bank [12].

With the new generation of TruPlasma Highpulse power supplies those effects will be minimized. The upper panel of Figure 9 shows the change of Ar and $N_2$ flow for TruPlasma Highpulse 4001 G2 operated in an average power regulation mode. Change of Ar/$N_2$ concentration has no influence on the stability of average power and average peak current values as shown in the middle panel of Figure 9. The Ar/$N_2$ concentration change influences the discharge parameters. The control algorithm, however, automatically adjusts the pulsing frequency to balance different average pulse voltage value at different gas ratio. This change is depicted in the lower panel of Figure 9 as the decrease of the duty cycle. As depicted in Figure 10 the change of the working gas from argon to nitrogen does not influence the current pulse shape. Compared to pulse in pure argon, HIPIMS pulses in Ar/$N_2$ and $N_2$ atmosphere have a slightly longer onset of the rising edge of the current, however, the difference is not higher than 5 µs. After this initial phase, the rest of the pulse waveform, i.e. from 40 to 200 µs, is kept similarly constant for all Ar/$N_2$ gas ratios thanks to the current pulse shape control algorithm implemented in new water-cooled TruPlasma Highpulse units. This gives the ability to maintain the stable peak current (or peak power) and ensure repeatable deposition conditions both in metallic and reactive sputtering.

It is worth to add, the stability of TruPlasma Highpulse G2 power supplies in the reactive conditions is also supported by improved arc management. The new generation of HIPIMS units is equipped not only with a standard current-based detector which reacts when output current exceeds user defined current threshold (Imax criterion), but also in UxI (cross detection) which allows much faster detection of an arc due to a simultaneous monitoring of voltage and current to fulfill corresponding $U_x$ and $I_x$ thresholds. A proper adjustment of arc management criteria settings allows to minimize the number of so called hard arcs detected by simple Imax current-based detector. Thus, as an arc is detected faster by the UxI criterion much less energy is provided into the arc hot spot inhibiting formation of macroparticles. This approach is depicted in the lower panel of Figure 9 where the temporal dependence of the arc counter (number of arcs) for two types of arc detection criteria: Imax and UxI are shown. The UxI and Imax detection criteria could be set to ensure arc detection and suppression first by UxI criterion for high process stability and improved coating properties.

## Conclusion

The experience gathered in the last decade of HIPIMS development allowed to equip the new generation of TRUMPF Huettinger units with unique features which guarantee high reliability and adjustability to different process requirements.

The key feature of TruPlasma Highpulse is the control of voltage and current pulse shape over whole length of the pulse. The preliminary experiments show noticeable influence of the pulse shape on the concentration of metal and reactive gas ions in plasma. The use of a controlled current pulse shape has been confirmed to influence of the deposition rate. In fact, the deposition rate can be further modified by the use of unique for TruPlasma Highpulse units possibility to regulate average power by automatic change of the pulsing frequency at constant peak current and pulse length time.

Regulation of a stable current during the whole pulse and the automatism of average power regulation shall find their application in HIPIMS reactive processes enabling convenient deposition control. Compared to earlier HIPIMS technology also the arc management has been improved for more efficient arc suppression.

With all these features the new generation of TruPlasma Highpulse power supplies is now mature for industrialization.

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## Author


- Dr. W. Gajewski


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Headquarters

© TRUMPF Hüttinger GmbH + Co. KG
Bötzinger Straße 80, D-79111 Freiburg
Phone: +49 761 8971-0
Fax: +49 761 8971-1150
E-Mail: Info.Electronic@de.trumpf.com

TRUMPF Huettinger Sp. z o.o.
Marecka 47, 05-220 Zielonka
Phone: +48 22 7613-800
Fax: +48 22 7613-801
E-Mail: Info.Electronic@pl.trumpf.com

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