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SHAPE MATTERS – BIPOLAR SPUTTERING

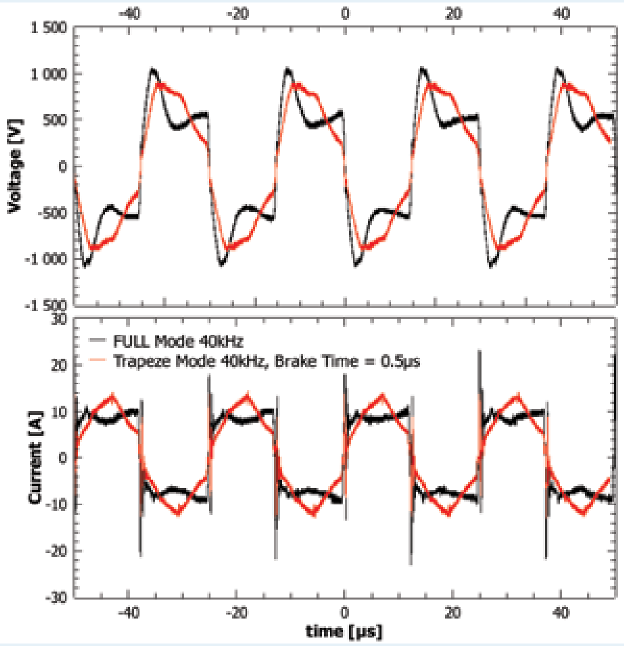

Figure 1: TruPlasma Bipolar (G2) current and voltage output in two operation modes: Full and Trapezoidal Mode at 40 kHz. For Trapezoidal Mode Brake Time of 0.5 µs was used

Background: Rectangular shape dual magnetron sputtering

Dual magnetron sputtering is a state-of-the art deposition technique in production of compound layers for glass coatings, functional films in electronic display technology or photovoltaic cells. Utilization of a pair of cathodes opened the possibility to industrialize large scale reactive sputtering by limiting the arcing probability as well as a by diminishing the disappearing anode effect. At the time when the dual magnetron sputtering was introduced to the community an attainable solution for a plasma power supply was a resonator circuit with sinusoidal output waveforms of current and voltage. However, in the last decade an alternative power delivery source for dual magnetron technology have emerged – the bipolar pulsed power supply, with a rectangular output shape of current and voltage [1].

Both the sine and rectangular power delivery techniques are designed to operate in the mid-frequency (MF) range (2 kHz – 100 kHz), with 40 kHz commonly used with sine MF power supplies [2]. Due to the technology background in the Bipolar power supplies, this units give a variety of possibilities to modify the delivery of power to the plasma. Three of those features of Bipolar power supplies are a) the possibility to modify the voltage and current pulse shape, b) the tunable pulsing frequency adjusted without mechanical changes in the unit, and c) the possibility to separate subsequent pulses with additional time, a Break Time, when plasma is turned off on both cathodes.

In Figure 1 different current and voltage output shapes available with the bipolar technology are depicted: (i) Full mode and (ii) Trapezoidal mode. In Figure 2 the Bipulse operation mode has been presented with different setting of the Break Time between the following positive and negative pulses. Current and voltage waveforms with the Brake Time length of 0.4 µs and 3.0 µs, have been shown as examples.

The benefits of the current and voltage waveform shape modification have been already discussed elsewhere [3], where the change of the output shape as well as the length of the Brake Time have been analyzed in terms of impact on the average plasma ion energy. The aim of this report is to provide essential knowledge to understand the idea behind the use of wider range of pulsing frequencies and the

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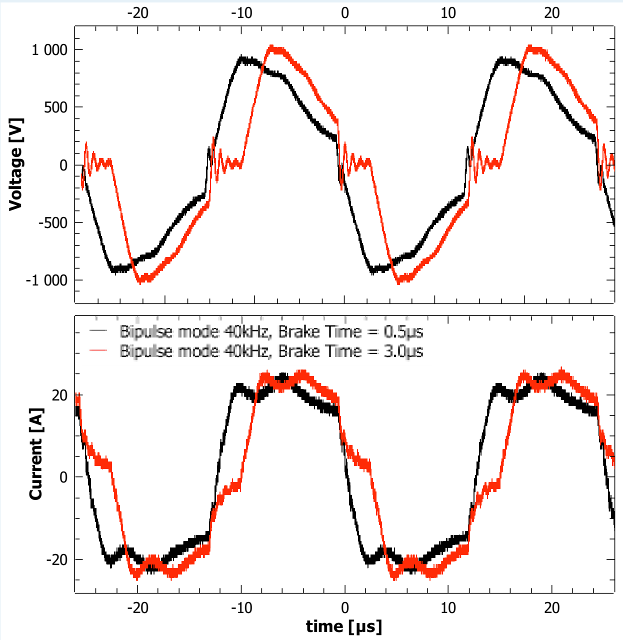

Figure 2: TruPlasma Bipolar (G2) current and voltage output in BiPulse Mode, 40 kHz and Brake Times of 0.5 µs and 3.0 µs

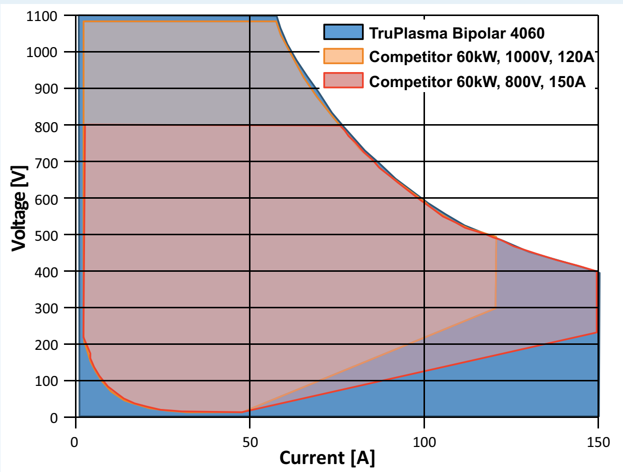

Figure 3: Power characteristic of the 60kW Power supply units: TruPlasma Bipolar 4060 (G2) and two competitors 60kW units with 1000V / 120A and 800V / 150A maximum output.

implementation of the Brake Time between the positive and negative half-wave in bipolar power supplies. Both functionalities will be discussed based on the data demonstrating their influence on the stability of the reactive sputtering deposition.

The challenge: Flexibility for process innovation

Continuous development of new coatings and products stimulates use of new materials and thus optimal methods for their deposition. The reactive sputtering of functional coating is widely used on industrial scale since the introduction of dual magnetron sputtering technique. Since few years sputtering from compound targets is gaining more popularity. This approach enables simplification of the process control, however, requires a high flexibility from the power supply. To enhance the processing modifiability easy accessible, different operation frequency and wide output power characteristics without current or power de-rating at high frequencies or low operation voltage are the key factors.

Most of the power supplies with rectangular voltage and current output available commercially on the marked can be used with frequency range between 0.5 – 50 kHz. Those units use, however, an electronic design known for AC sine power supplies with all limitations resulting from this solution. The effect of such design is depicted in Figure 3, where the power characteristic of the TruPlasma Bipolar 4060 (G2) power supply (60kW, 1000V, 150A) has been compared with characteristic of other vendor's power supplies. Note, that due to the special design of the TruPlasma Bipolar its power characteristic extends over power characteristic of two different competitor's power supplies. Furthermore, the TruPlasma Bipolar allows operation with low voltages and high current, a feature which might be necessary for reactive sputtering of materials with high secondary electron emission yield [5]. In addition the TruPlasma Bipolar units can be used with pulsing frequencies higher than 50 kHz, namely 60 kHz, 80 kHz and 100 kHz, with no limitation on the maximum nominal output current in the whole frequency range.

Case-study: Reactive sputtering from compound target

In order to obtain an unequivocal picture of the benefits of the wide frequency range and Brake Time available in the TruPlasma Bipolar 4000 (G2) power supplies experiments with a Si(Al)ZnOx dual rotatable magnetron were carried out. The aim of the study was to

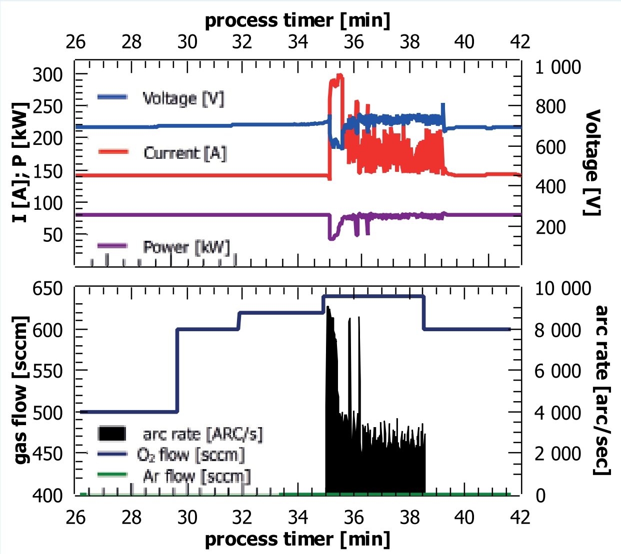

Figure 4: Effect of Bipolar pulsing frequency: time evolution of process parameters for 80 kW, 40 kHz process. In upper panel discharge parameters (Voltage, Current, Power) are shown. The lower panel presents the gas flow (Ar and O_2) and the resulting arc rate during the experiment.

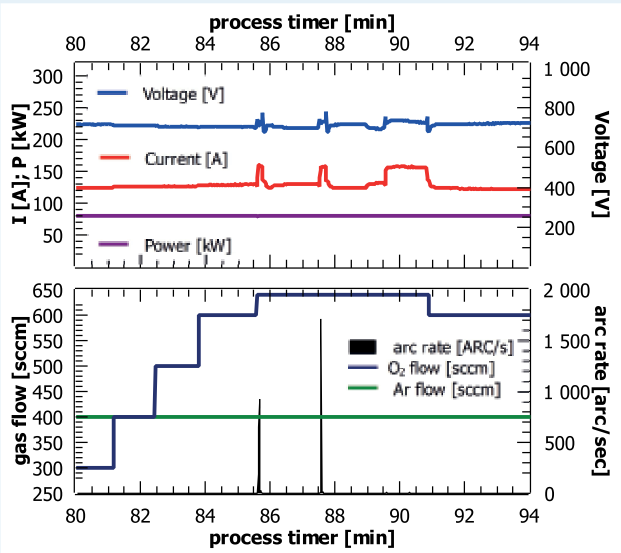

Figure 5: Effect of Bipolar pulsing frequency: time evolution of process parameters for 80 kW, 80 kHz process. In upper panel discharge parameters (Voltage, Current, Power) are shown. The lower panel presents the gas flow (Ar and O_2) and the resulting arc rate during the experiment.

demonstrate:
a) the influence of available pulsing frequency on the stability of the reactive sputtering process from compound target, and
b) the influence of the additional Brake Time between the positive and negative half-wave on the probability of arcing during reactive sputtering.
The experiments were performed on a standard in-line glass coating system (von Ardenne) with cylindrical cathodes 3750 mm long. The voltage and current were monitored at the power supply output and the process parameters were recorded by the diagnostic software PVDPower available with the power supply unit.

The effect of pulsing frequency

As mentioned above typical pulsing frequency used in sine and bipolar power supplies in dual cathode arrangement is 40 kHz [2, 4]. Figure 4 depicts the process parameters recorded during the test performed with TruPlasma Bipolar power supply at 40 kHz with constant power of 80 kW. In order to achieve the output power of 80 kW required due to the size of used magnetrons, two TruPlasma Bipolar 4060 (G2) units were operated in parallel mode providing a maximum output power of 120 kW, maximum output voltage of 1000 V and maximum output current of 300 A. The lower panel of Figure 4 shows the flow of argon and oxygen. For oxygen flow below 640 sccm the process is stable. As the oxygen flow reaches 640 sccm process runs into the reactive mode which is directly reflected in the abrupt increase of arcing (lower panel). At the same time current, voltage and power get unstable due to arcing and arc suppression by power supplies. Although after 2-3 minutes of heavy arcing the arc rate saturates at about 3000 arc/sec and process can be continued thanks to fast arc detection and suppression algorithms, such high arcing conditions can be undesired from the perspective of parameters of deposited film.
In the case it would be necessary to operate at given gas flow and power parameters use of 40 kHz or even slightly (±20 %) higher frequency is not enough to stabilize the process. In this case, however, it can be beneficial to double the frequency as shown in Figure 5. Figure 5 presents the process data measured for similar power as well as argon and oxygen flow as in Figure 4. Here, however, the pulsing frequency was set to 80 kHz. As the graph reveals at doubled frequency process can be operated smoothly in the reactive mode. Due to a higher pulsing frequency the discharge is turned off at both cathodes more often thus lowering the probability of arc formation. Indeed, arcing almost vanishes and only two single arc rate peaks can be resolved in the lower panel of Figure 5. They are however, of much lower intensity (>2000 arc/sec) compared to the arc rates recorded at 40 kHz and their duration is less than 5 seconds.
A possibility of stable operation at increased frequency can be also demonstrated in the process operated in constant voltage as shown

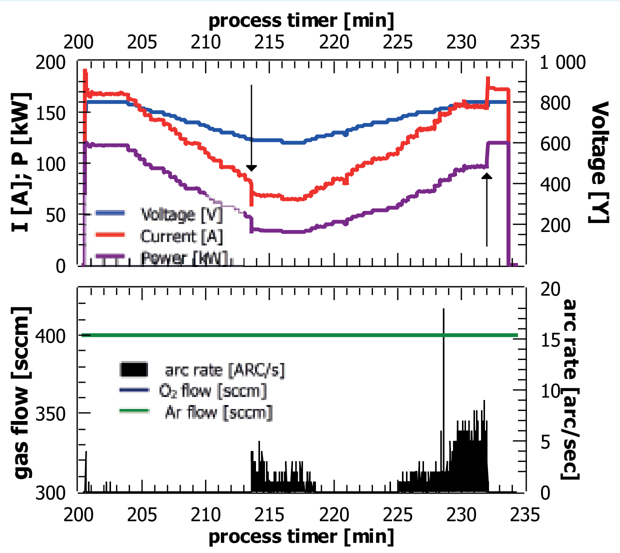

Figure 6: Effect of Bipolar pulsing frequency in Voltage Regulation: time evolution of process parameters for 120 kW, 80kHz process. In upper panel discharge parameters (Voltage, Current, Power) are shown. The lower panel presents the gas flow (Ar and O_2) and the resulting arc rate during the experiment.

in Figure 6. For this experiment the starting voltage was adjusted to keep the process close to the transition mode at 800V, 120 kW and gas flow Ar: 400 sccm, O_2: 400 sccm, respectively. Than the voltage was decreased in steps of 10 V down to 610 V which corresponds to the operation at fully poisoned conditions. Afterwards the voltage was increased until the power reached again 120 kW at 800 V. The arrows indicate the change to poisoned mode at about 214 minute of the process and to metallic mode at about 232 minute of the process. Due to high pulsing frequency arc ratio did not reached more than 20 arc/sec during the whole experiment which allowed a stable operation throughout the whole hysteresis loop.
These simple examples undeniably demonstrate the advantage of use of higher than standard frequencies in reactive sputtering of compound materials.

The effect of additional Brake Time

In the case of established processes when the Bipolar power supply shall be used as a replacement of an old unit, the Bipolar technology gives another functionality to control the stability of a process at a fixed frequency: Break Time between positive and negative half-wave of current and voltage. The influence of the Brake Time in the Bipulse Mode (Figure 2) of TruPlasma Bipolar power supply has been reported in Figure 7. Process was run at fixed power of 50 kW and pulsing frequency of 40 kHz. The gas flow of argon and oxygen was also fixed at 400 sccm and 450 sccm, respectively. One parameter changed during the experiment was the Brake Time within the accessible range of 0.4 to 5.0 µs, represented in the lower panel of Figure 7 as orange line. Change of the Brake Time length from 0.4 µs to 5.0 µs has a strong influence on the stability of the process: at shortest brake time (0.4 µs) arc rate is higher than 5000 arc/sec and process current and voltage drift with time. Increasing the Brake Time length to 1.0 µs and 3.0 µs results in a reduction of the arc rate to 3600 arc/sec and 2700 arc/sec, respectively. For the longest Brake Time of 5.0 µs the arc rate is further reduced to 1900 arc/sec, thus stabilization of process parameters, i.e. voltage and current, can be observed.
The observed reduction of arcing with an additional Brake Time between positive and negative half-wave can be compared to the influence of Pulse-Off time used in Pulsed-DC sputtering technology. Until today numerous reports have confirmed the use of Pulse-Off time in the Pulsed-DC sputtering as an effective way to increase the long term stability of the deposition of Al_2O_3, SiO_2 or TiO_2 [4]. Introduction of a Brake Time in the Bipolar sputtering which is possible only with power supplies working with a rectangular output shape of current and voltage gives an additional time for electrons from plasma to reach surface of both targets, thus discharging the surface of electrode which will be a cathode in the next pulse as well as the surface of electrode which in the next pulse will serve as an anode. This in turn leads to a decrease of arcing as observed in the results in Figure 7.

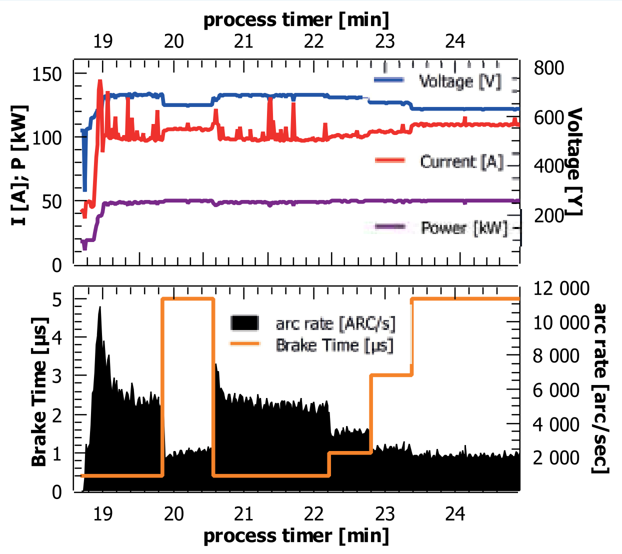

Figure 7: Effect of Bipolar Brake Time: time evolution of process parameters for 50 kW, 40 kHz process. In upper panel discharge parameters (Voltage, Current, Power) are shown. The lower panel presents the length of Brake Time and the resulting arc rate during the experiment. Constant gas flow of Ar: 400 sccm and O_2: 450 sccm was used.

Conclusion

The possibility to increase the productivity of the deposition process is one of the most important factors for industry. One of the method to achieve this goal is the use the most up-to-date technique for delivery of power and control of the plasma discharge. In this paper two features of Bipolar power supplies were presented: (i) wide pulsing frequency range (up to 100 kHz), and (ii) an additional Brake Time between the positive and negative half-wave of the rectangular waveform of current and voltage. Both features have demonstrated their strong potential in the stabilization of the reactive sputtering by reducing the tendency of arcing. It was shown that doubling the standard operation frequency to 80 kHz allowed to keep the process stable even in the poisoned mode. On the other hand a significant reduction of arcing was also possible at lower bipolar pulsing frequency (40 kHz) if the output voltage and current waveform is modified by a Brake Time between the positive and negative half-wave. Therefore, a combination of higher pulsing frequency and additional Brake Time with fast and accurate arc detection mechanisms can be used as powerful method of sputtering process optimization.

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