generating knowledge

ARC-MANAGEMENT

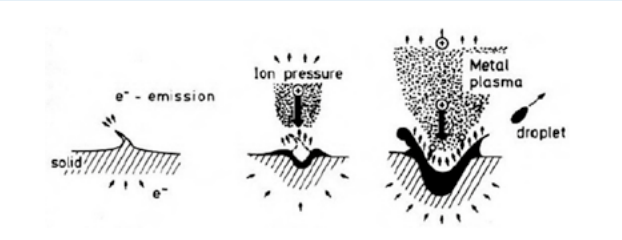

Fig. 1. Microscopic model of cathodic arc formation [2].

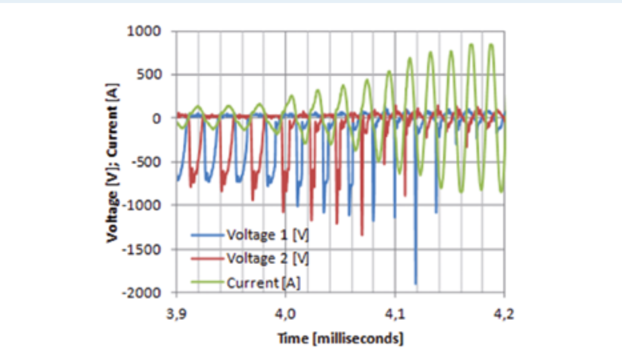

Fig. 2. MF current and voltage waveform during the transition to a cathodic arc (approx. 3.99ms) and to a thermionic arc (approx. 4,14ms). No arc treatment.

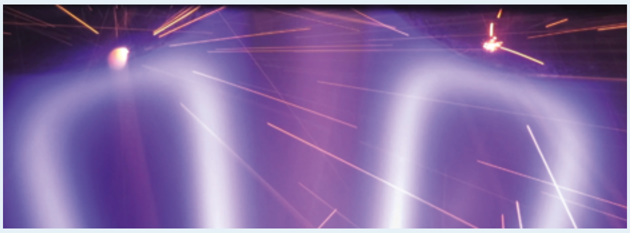

Fig. 3. Thermionic arc between two rotatable magnetron cathodes with stable cathode spots and material ejection, visible as spark traces. No arc treatment.

Background: The origin of arcs in MF magnetron sputtering

A well known problem in reactive magnetron sputtering is arcing at the cathodes. This is for two primary reasons: (1) the magnetron plasma is operated at high current densities, thus favoring a transition from the abnormal glow to an arc. (2) Due to the addition of oxygen or nitrogen, the cathode surface is never quite metallic, but partially or completely covered by absorbed gas. A dielectric layer (oxide, nitride) promotes the glow-to-arc transition with locally very high current densities. This was found in early plasma physics research [1].

The properties of an arc discharge are primarily determined by processes at the cathode spot. The initial step in arc formation is the local collapse of the cathode fall by a locally high current density; this is an extremely non-stationary and self-augmenting process. An illustrative microscopic model of the arc formation is shown in Fig. 1. The initial cathode spot is shown in the left figure as a small protrusion like it would be found at the rim of a previous arc crater. It could be however originating from any inhomogeneity, like a local oxide spot or some foreign body on the surface. At the cathode spot, not only electrons are emitted due to the electric field enhancement, but the temperature and pressure gradient also leads to ejection of ionized cathode material. Due to the highly non-stationary characteristics, an arc can develop in very different ways: a cathodic arc is characterized by frequent extinction and re-ignition of the cathode spot. Therefore, it often extinguishes during the polarity change at MF voltage thus leading to a short increase in current with simultaneous collapse of the cathode voltage, followed by a return to the normal process state in the next MF periods. However, the arc may also re-ignite with each following half cycle, as shown in Fig. 2, and finally form stable and hot surface spots, resulting in a transition from a cathodic to a thermionic arc. Thus a conductive plasma channel forms with stationary cathode spots, where the cathode material melts and evaporates (Fig. 3).

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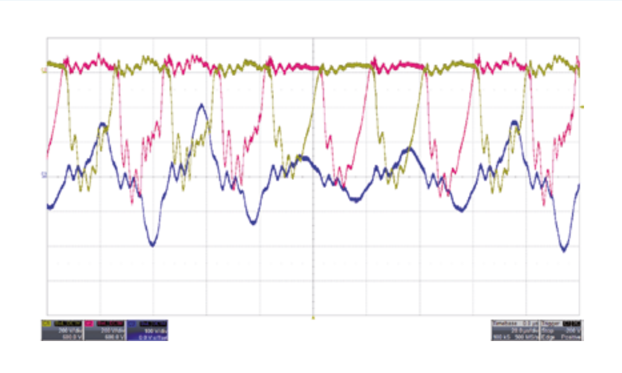

Fig. 4. Example of an unstable process state (Al planar, O2). Red, brown: cathode voltage, blue: current.

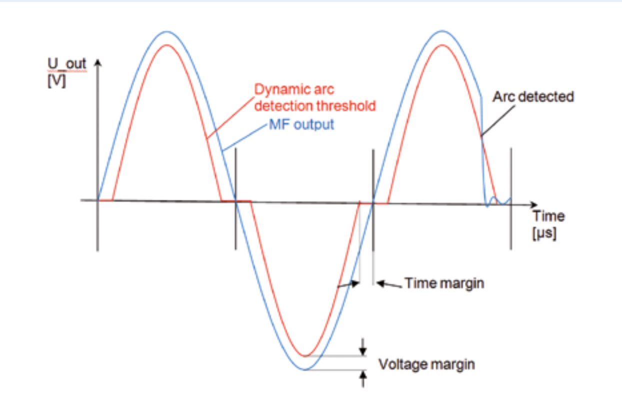

Fig. 5. Real-time arc detection by comparing the voltage waveform with the waveform of the previous period.

Requirement to the power supply: arc detection and extinguishing

The arc treatment presents some challenges to the plasma generator: (1) the current rise or collapse of the cathode voltage must be detected as fast and reliably as possible, in the example of figure 2 this should be at 3.99ms; (2) the plasma generator must shut down the output power very quickly, preferably within a few microseconds and (3) reach full power again within a few half-waves (<100us). This leads to two important parameters for the arc treatment: the detection time, i.e. the time from ignition of the arc, recognizable by the first drop in cathode voltage and current increase until the internal trigger signal "arc detected" is set and secondly, the reaction time until the power module shuts down.

Reliable arc detection must not only be fast, it also must neither miss arcs, nor must it interpret a sudden change of target impedance as arc. In practice, this is complicated by the severe distortion of the current and voltage waveforms under different process conditions. Occasionally, high frequency oscillations are induced; this may be associated with plasma wave formation in the race track [3]. Also, target coverage and impedance may change every few half-waves. A practical example of unstable target voltage and current signals is shown in Fig. 4.

TruPlasma MF Series 7000 (G2): intelligent arc detection in real time

The key to fast and reliable arc detection by the new generators TruPlasma MF Series 7000 (G2) is the real-time data acquisition and processing. As shown in Fig. 5, a reference (shown in red) is formed from the previous half-wave of the same polarity, shifted by the parameters "Voltage margin" and "Time margin". The actual waveform (shown in blue) is compared with this reference, so that the collapse of the cathode voltage or an increase in the current (not shown) can be detected immediately, indicated by "arc detected" [4, 5].

In the case of a strong and rapidly varying waveform distortion by the plasma, which prevents a direct comparison of waveforms, further detection methods are available. These also trigger the arc treatment during or immediately after the relevant half-wave.

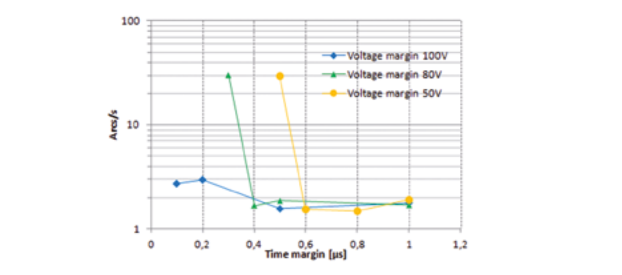

Fig. 6. Measured arc rates for different settings of the arc detection parameters "Voltage margin" and "Time margin". The real arc rate was 2 – 3 arcs/s, higher values are the result of false detections when parameters are set too sensitive.

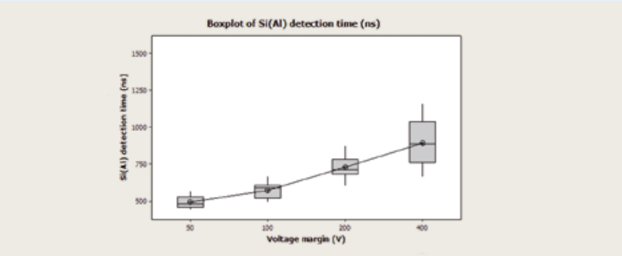

Fig. 7. Effect of the selected "Voltage margin" on the detection time. Target Si(Al). "Time margin" was set at 1µs.

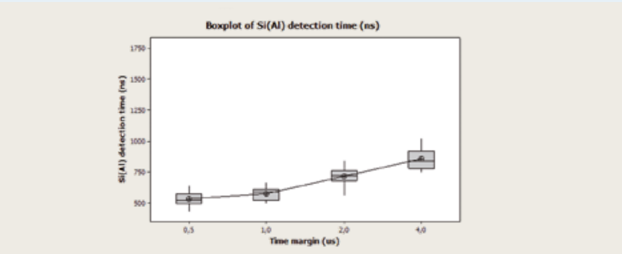

Fig. 8. Effect of the selected "Time margin" on the detection time. Target Si(Al). "Voltage margin" was set at 100V.

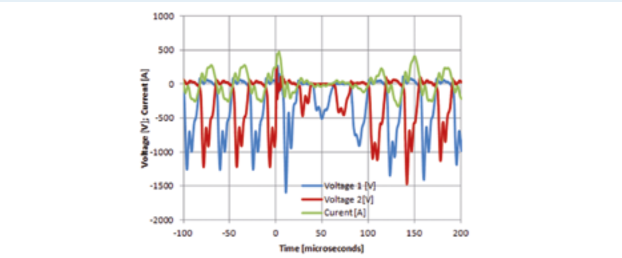

Fig. 9. Signal traces for the arc handling method "FastTreatment", showing decay and re-start of plasma current and voltage.

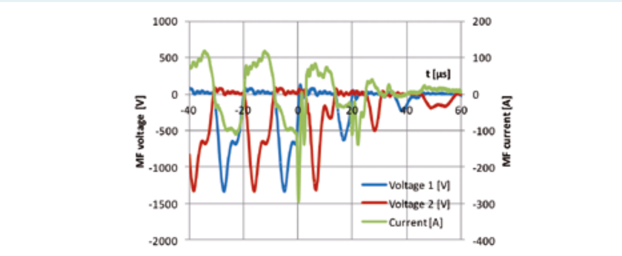

Fig. 10. Example of the signal traces for the arc handling method "FastTreatment" in the case of arc re-ignition during current decay.

For arc detection immediately after starting the generator, no reference signal as in Fig. 5 is available, so that an absolute maximum limit for the peak current must be set.

Typically, the time from the first break-down of the cathode voltage or current rise to the internal arc detection is less than one microsecond.

To find appropriate values for the detection parameters "Voltage margin" and "Time margin", the apparent arc rate may be used. If either value is set too sensitive, the apparent arc rate, shown by the arc counter, rises significantly due to false detections. The apparent arc rate for various combinations of "Voltage margin" and "Time margin" is shown in Fig. 6. The actual arc rate in the example is 2 to 3 arcs/s. The actual settings are relatively uncritical: as Figs. 7 and 8 show, the time between first ignition and detection is only weakly dependent on the selected "Voltage margin" and "Time margin". Thus, in the example shown in Fig. 7, values from 50 to 200V for "Voltage margin" are suitable with only a slight increase in detection delay. A similar relation is shown for "Time margin" in Fig. 8.

TruPlasma MF Series 7000 (G2): ultra fast arc blanking, minimal disruption of the process

For the fastest possible arc extinction two options are available:

(1) "FastTreatment": the energy supply to the resonant output tank circuit is interrupted, so that only the energy stored therein is delivered to the plasma. An example is shown in Fig. 9. In this case, the self-extinction of the arcs at polarity change takes effect, so that the arc usually only lasts until the end of the actual half-wave. In the following half-waves, the cathode fall is again present, a sign of arc extinction. Since most arcs ignite during the second half of a half-wave, this means that at operating frequencies of 25 – 70 kHz an arc can be extinguished after typically 3 – 10 µs. Thus a fast arc treatment is already achieved. However, there is a certain risk of re-ignition during the remaining oscillations of the tank circuit, resulting in further current peaks. An example of the resulting signal is shown in Fig. 10.

(2) "UltrafastTreatment": a switch in the output circuit cuts the power to the plasma, dissipating the energy in the output circuit. The intervention of the switch begins typically

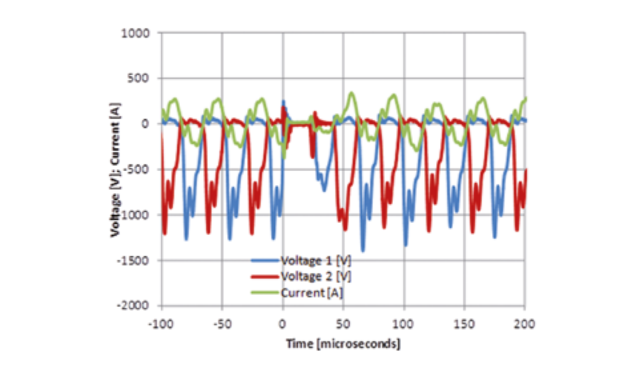

Fig. 11. Signal traces for the arc handling method "UltrafastTreatment". The current is shut down within 3µs and reaches set value after 50µs.

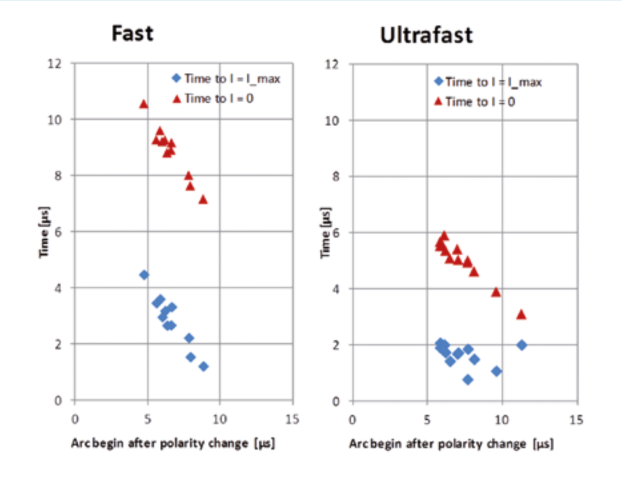

Fig. 12. Comparison of the arc treatment time without switch "FastTreatment" and with switch "UltrafastTreatment". Blue: time between arc ignition and beginning of current shut-down for "UltrafastTreatment" or current maximum for "FastTreatment", red: time to I = 0A. Si(Al) rotatable targets, 100kW reactive (O2), 38kHz.

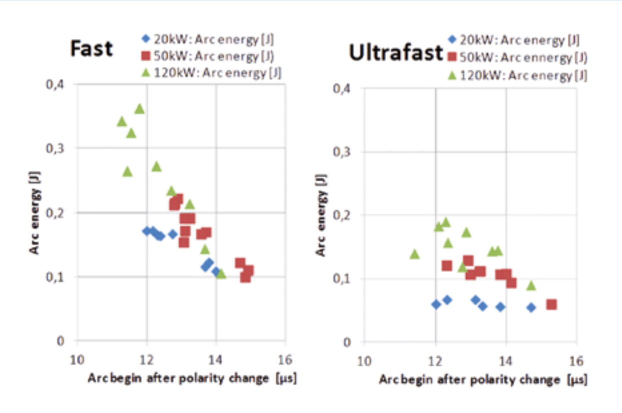

Fig. 13. Arc energy for TiOx rotatable targets at 20, 50 and 120kW generator power. The energy depends mainly on the ignition moment during the half wave.

1.5 - 2µs after arc ignition and 0.8 - 1,3µs after internal arc detection. An example is shown in Fig. 11.

The rapid detection in conjunction with the function "UltrafastTreatment" prevents any heating of the cathode spots and therefore allows restarting the generator after 20 – 50µs without re-ignition of the arc. Thus operation is ensured even at high arc rates without appreciable loss of average power and deposition rate and without the possible drift of the operating point. A comparison of the measured response times of "FastTreatment" and "UltrafastTreatment" is shown in Fig. 12 as a function of the time from zero crossing to arc ignition. With "FastTreatment", the time to I = 0A corresponds to the end of the half wave or the following polarity change, unless the arc re-ignites as shown in Fig. 10.

TruPlasma MF Series 7000 (G2): arc energy

If the power delivered after arc ignition is integrated, the arc energy may be determined. However, some sources of error arise: (1) the current and voltage must be measured close to the target and not at the generator, since otherwise the result is unusable due to signal propagation delay and cable oscillations. (2) The transition from glow discharge to arc is certainly not sharp. During the collapse of the cathode fall a part of the power is still delivered to the glow discharge. However, the beginning collapse of the cathode fall and the current rise mark the only objectively measurable time for the arc beginning. The integration from the ignition thus represents an upper limit for the actual arc energy. (3) If it takes more than one half-wave for current and voltage to reach zero, it must be decided for each half cycle on the basis of waveform, whether the arc re-ignites after polarity change as shown in Figs. 2 and 10, or whether the cathode fall and glow discharge is re-established as shown in Fig. 9 and the arc is extinguished after polarity change.

The arc energy depends only slightly on the actual generator power, as the example in Fig. 13 shows. A power variation by a factor of 6 leads only to a doubling of the arc energy. Occasionally, the arc energy is specified relative to the output power [7]. In fact, an arc is an event the power and energy density of which largely depends on the physical processes in the arc and only within limits on the output power or power rating of the generator. The arc energy / power (usually specified in mJ/kW, i.e. in microseconds) is only of limited usefulness as a specified power supply parameter, what counts is the detection and response time of the generator.

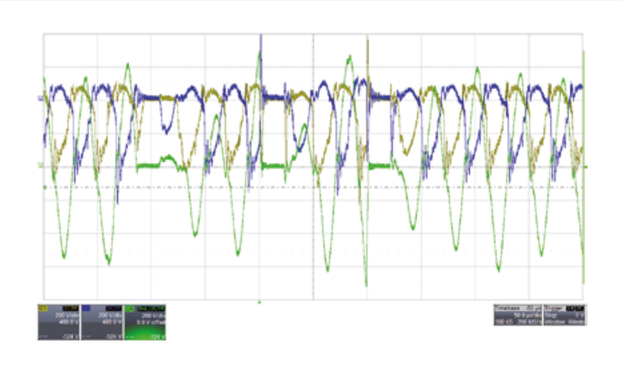

Fig. 14. Example of frequent arc blanking with "UltrafastTreatment". Within 300µs three arcs were treated (horizontal scale = 50µs/div.).

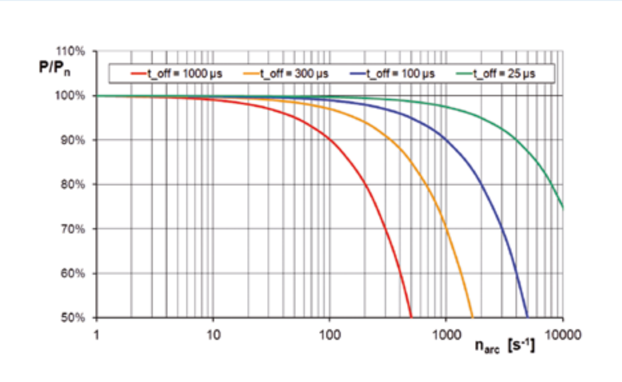

Fig. 15. Relative loss of average power as function of the arc rate and the blanking time (t_off).

Based on the rated output of 150kW of the generator used for the results in Fig. 12, normalized arc energies in the range of 1mJ/kW$_{rated}$ are surely possible.

TruPlasma MF Series 7000 (G2): arc rates

The generator can extinguish a maximum of about 8000 arcs per second. This is necessary if, as shown in Fig. 14, an arc ignites during re-start after arc treatment. However, certain restrictions do apply: for short periods this is necessary for heavily arcing targets, e.g. 8 arcs in 1 millisecond. If the generator is operated near the power limit, this is only briefly practical: during permanent blanking of 8 arcs/ms too little average power is available for a stable process. The calculated loss of average output power at high arcing rates is shown in Fig. 15 as a function of the blanking time. The advantage of short blanking is immediately apparent here.

In the event of prolonged arc cascades that prevent stable operation, the generator attempts to stop them by extending the break time after repeated blanking events.

Especially at high arcing rates the "UltrafastTreatment" function provides a major advantage: By rapid and short blanking at high output currents it allows a much quieter operation at rates in the range of 500 arcs/s. Because of the high arcing tendency of heavily worn targets, this results in a significant cost advantage through improved target utilization.

This very fast arc treatment provides unique advantages over the slower treatment of other power supplies, where the power lost during blanking needs to be compensated by temporarily raising the set-point.

TruPlasma MF Series 7000 (G2): technical progress

The methods described here are the result of the continuous improvement of our proven technology in flat panel display manufacturing. Due to the ultra-fast arc detection and the robust arc switch in the "UltrafastTreatment" function, the technology is now also available in the high-power range and thus for architectural glass coating.

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[3] M. Siemers, A. Pflug, B. Szyszka, "Particle-in-cell Monte Carlo analysis of propagating plasma waves in DC magnetron discharges" 52nd SVC Annual TechCon Proc., (2009) pp. 13-16
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