generating knowledge

SINE OR SQUARE WAVE

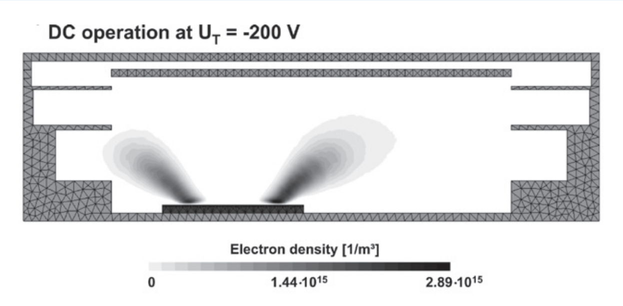

Fig. 1: Simulation of the electron density in a DC sputtering plasma [10].

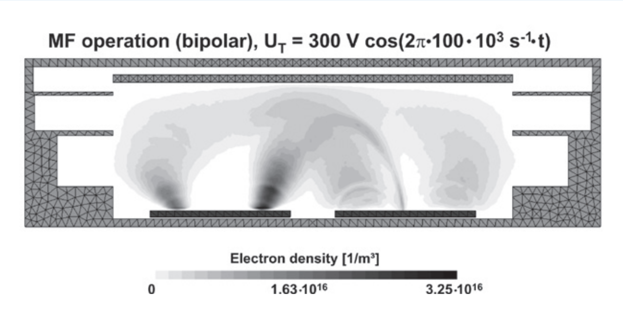

Fig. 2: Simulation of the electron density in an MF-double magnetron sputtering plasma [10].

Background: Relevance of the signal shape to pulsed magnetron sputtering

Since the introduction of dual-magnetron sputtering (DMS) for highly insulating layers there is the choice between square wave pulse or sine wave power supplies. Even at an early time it has been argued that a bipolar square wave generator is more flexible with respect to symmetry and duty cycle, but that sine wave generators are easier to implement for high output powers. Also it has been suggested that the square wave generators could be less reliable due to the lack of a resonant output circuit separating the switching components from the plasma load [1,2].

Today, both types of generators are available in a wide power range and modern sine wave generators are equivalent to their square wave counterparts with respect to the arc management speed and low arc energies [3,4]. For this reason, the decision can mainly be made on the basis of economic (investment, operating costs) and technical data (matching range, process flexibility). In the following we will investigate whether there is a fundamental influence of the waveform on the coating result (rate and properties), which ought to be taken into consideration when selecting the power supply. For this purpose, we first give an overview of published results. The main focus is then a direct comparative study of titanium oxide reactive sputtering from metal targets.

Pulsed magnetron sputtering, both unipolar and bipolar, has established itself as a key technology for the production of dielectric and highly insulating layers. For the advantage of pulse sputtering, as compared to DC, two reasons were identified: First, the periodic discharging of the target surface and the extinction of arcs between the pulses or during polarity changeover allows the deposition of defect-free layers in unprecedented quality and rate [1,5]. Secondly, it was recognized that the pulse edges lead to high electron temperatures in the plasma and an energetic ion flux to the substrate surface, which also leads to the growth of compact and fine-grained films [6,7]. This suggests that the influence of the ions on the film growth ought to increase with the pulse frequency and shorter rise times. In fact, an increase in thermal load to the substrate with frequency was observed [6], but the influence on the film properties is comparatively low [7].

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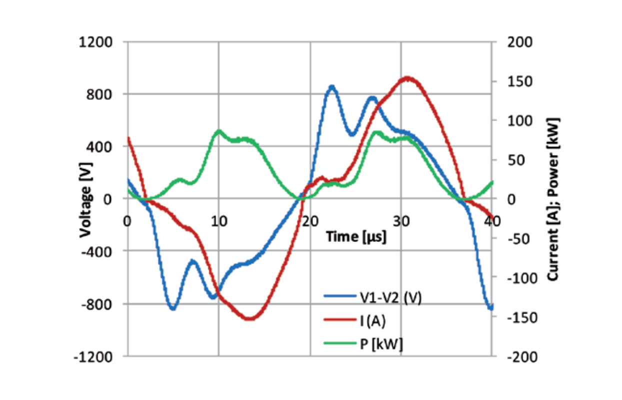

Fig. 3: Example of current, voltage and instantaneous power with a sine wave generator (40kW, 524V, 96A).

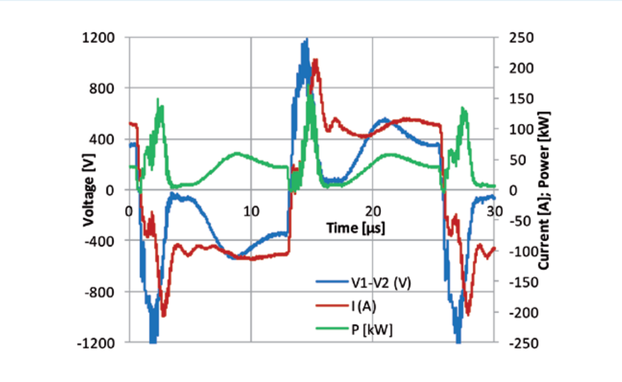

Fig. 4: Example of current, voltage and instantaneous power with a square wave generator; target and process conditions as in Figure 3 (40kW, 490V, 100A).

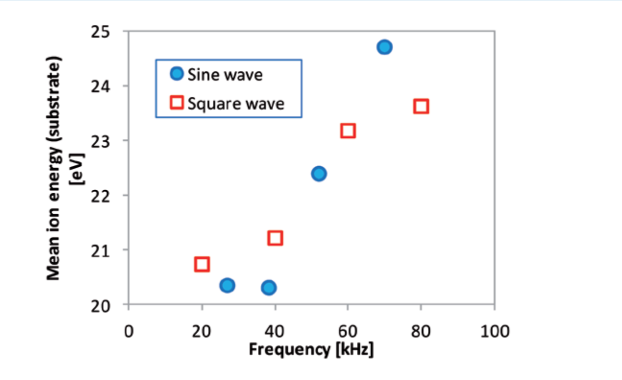

Fig. 5: Mean ion energy on the substrate, measured with a retarding field analyzer.

A fundamental difference between unipolar pulsed sputtering and dual magnetron sputtering (DMS) is the use of a magnetron as the anode. Apart from the fact that the anode then is not covered by an insulating layer due to the alternating sputtering from the two targets, it is also magnetically shielded so that electrons can reach there only along the field lines[1]. Consequently, in DMS, the plasma density in front of the substrate and thus the ion flux is higher than with a non-magnetic anode, the ion current density and ion energy being mainly determined by the field strength of the magnetron [8]. With DMS significantly harder layers have been achieved as compared to unipolar pulsed sputtering [9]. This shielding effect is also impressively illustrated by simulations, shown in Figure 1 and 2 [10]. When DC sputtering, the electrons are concentrated above the race tracks of the cathode. In DMS the current path is perpendicular to the anode (right magnetron), through which the plasma is pushed towards the substrate.

Sometimes it is argued that a square wave generator is the best choice for reactive sputtering, as it will deliver voltage, current and power at approximately 100% duty cycle during each half-wave. Ideal waveforms are seen with a resistive load, however, in a real magnetron installation, the waveforms may be significantly distorted as shown in the examples of Figure 3 for a sine wave generator and in Figure 4 for a bipolar square wave. Thus there is no "quasi DC".

Background: Current state of knowledge regarding the effect of signal shape on the coating process

There are only few publications on the influence of the power waveform on the coating result. In [11] the authors compare planar and rotary targets powered with sine and bipolar pulsed supplies. The conclusion is for reactively sputtered TiO_2 that the influence of the power supply type on layer properties is small, whereas the target type is more relevant. A comparison of square and sine wave for sputtering ITO from an In(Sn) target is presented in [12]. ITO is a particularly sensitive layer system with respect to the plasma parameters, since both the light absorption and electrical conductivity are very sensitive to the conditions during deposition. The waveform resulted in some differences in electron temperature and density near the substrate, but the film properties (optical absorption, el. resistivity) and the structure (X-ray diffraction) did not depend significantly on the exciting wave form, as long as the same electron density near the substrate was selected. In a comparison of HfO_2, sputtered with a bipolar pulser and MF sinus, the latter showed a slightly higher refractive index [13].

1) The earth's magnetic field has a similar shielding effect, so that charged particles penetrate only at the poles into the atmosphere and cause the aurora.

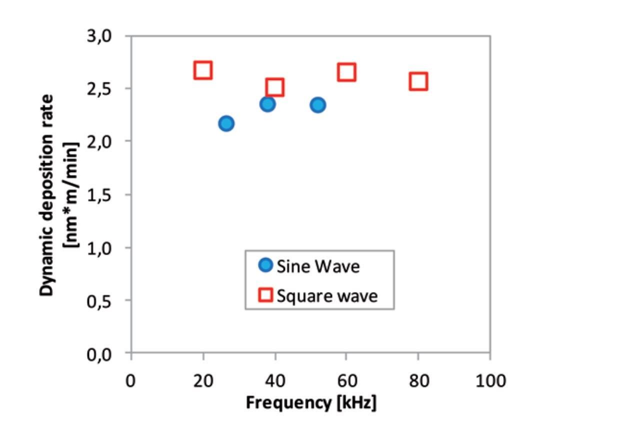

Fig. 6: Comparison of deposition rate as a function of frequency for sine and square wave excitation of the DMS sputtering plasma

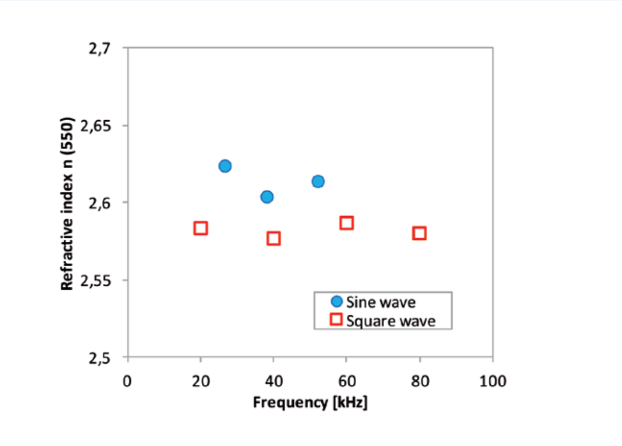

Fig. 7: Values of the refractive index at 550 nm wavelength for the layers in Figure 6.

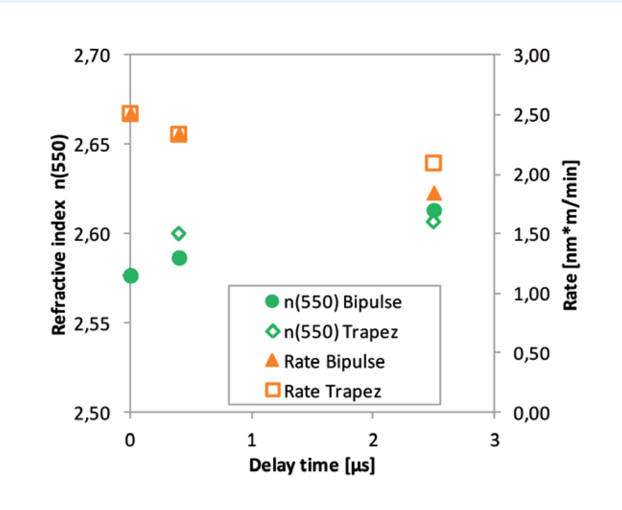

Fig. 8: Dynamic deposition rate and refractive index for the square wave generator as a function of delay time.

Case Study: Comparison sine vs. square wave for TiO_2

In order to obtain a clearer picture of the possible influence of the waveform, a comparative study on reactive sputtering of TiO_2 from planar metallic targets was carried out. It was conducted on the Leybold A700V in-line sputtering system of the Fraunhofer IST in Braunschweig. The MF power was kept constant at 10 kW with 750 mm target length. For electrical process characterization, currents and voltages were recorded at the cathodes and the ion flux in the substrate plane was measured with a retarding field analyzer. Films were deposited and characterized optically by transmission and reflection measurements and on selected samples by ellipsometry as well as structurally by X-ray diffraction.

Figure 5 shows the average ion energy for both generators to increases with frequency. This is consistent with previously reported finding that high-energy ions are generated at each polarity change, so that their share in the total flux is higher at high frequencies. Both generators behave similarly in this respect.

The (dynamic) deposition rates are compared in Figure 6. The influence of the frequency on the rate is low, as it was already reported [1,14]. The square wave generator shows a slightly higher deposition rate. The refractive index or optical density shows the opposite trend. As Figure 7 shows, here the values for the sine wave generator are slightly higher. In optical coatings, the target is often the so-called optical thickness, the product of refractive index with thickness n*thk. Taking into account that under practical conditions several factors in a coating process can affect the refractive index and rate, the differences shown here are not really significant.

With the square wave generator, some control of the output shape is available. By setting a delay time in the "Bipulse" or "Trapezoidal" modes, the changeover between positive and negative half waves may be delayed; the signal shape thus becomes more similar to a sine wave. As Figure 8 shows, the coating result is then also altered: The refractive index increases with increasing delay time and the rate decreases, so that the values approach those of the sine wave power supply. Zero delay time corresponds to the regular square wave operation here.

Examination of the samples by X-ray diffraction showed the differences in refractive index observed here to be determined by the ratio of rutile to anatase. The rutile content is about 63% for samples with a refractive index of 2.58 and at about 70% for samples with n of 2.64.

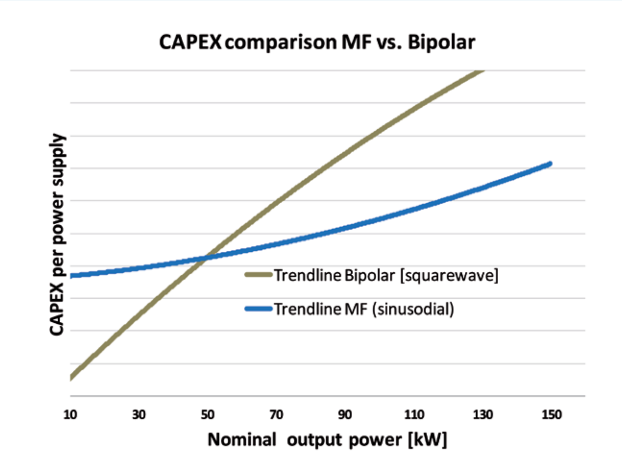

Fig. 9: Function of the investment costs for each generator as a function of nominal output power.

Conclusion: Basis for decisions on the power supply type

▪ The current experimental findings are consistent with the few data in the literature: There is some influence of the waveform on the thin film growth, but it is expected that other unavoidable factors, such as the changing magnetic field with target erosion are much more pronounced. Therefore, the differences found are virtually irrelevant for the choice of power supply.

▪ In generators of the latest generation the arc management is equivalent and therefore not relevant to the decision.

▪ The decision for a certain type of generator can therefore be made on the basis of economic considerations. For illustration, the CAPEX for a power supply is shown as a function of the rated output power in Figure 9. For low power ratings up to 50kW bipolar square generators are usually the better alternative. Here the flexibility with regard to simple frequency changing and signal shape is useful. For industrial coating systems with high coating widths and power levels, the MF generators are never the less a better choice.

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