generating knowledge

VOLTAGE CONTROLLED TRANSITION MODE

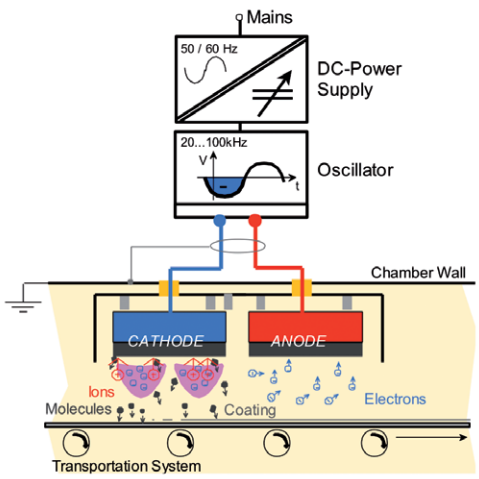

Figure 1: Principle of dual magnetron MF sputtering.

Background: Why reactive sputtering?

Reactive sputtering is a widely successful method for depositing insulating and hard coatings in modern industry. Compared to evaporation, sputtering offers the advantages of ion supported deposition [1], rendering it industrially attractive in spite of considerable equipment and electricity cost.

The prime requirements to such coatings are high dielectric strength, insulation resistance and hardness. This is the opposite of the desired target materials properties: Electric conductivity and tolerance to thermal stress and power cycling.

For some materials, suitable conductive oxides are available (TiO_x, Zn(Al)O). For two of the two most important dielectrics, SiO_2 and Al_2O_3, a cathode fall for efficient sputtering can be realized in front of an oxide target only by expensive RF technology. In addition, the sputter yields (sputtered atoms / incident ion) are very low. The solution is to use a metal target in a reactive atmosphere: Electric and thermal conductivity, ductility of metals and the high sputter yield allow high sputter rates.

The difference in sputter yields between metal and oxide leads to the well known hysteresis in reactive sputtering: Upon adding oxygen to the sputtering atmosphere, it is incorporated into the coating as desired. If the oxygen is not completely consumed in the coating, it oxidizes the target surface. This reduces the sputtering rate and self-cleaning capability of the target surface, giving positive feedback to the oxidation rate. The target surface is rapidly „poisoned“. This leaves us with the choice between high deposition rates yielding useless absorbing sub-oxide coatings (metallic target) or good dielectric coatings at low sputtering rates (oxidized target). The hysteresis has been described theoretically in the Berg model [2]. MF-driven dual magnetrons, shown in Figure 1, are the preferred choice for reactive sputtering of dielectric coatings. Their advantages are avoiding process drift due to insulating coating on the anode and self-extinguishing of arcs during polarity change.

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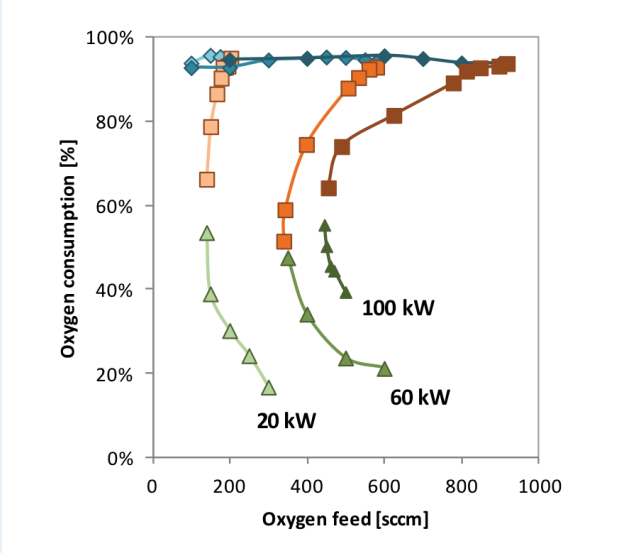

Figure 2: Oxygen consumption during reactive sputtering from a 3.75 m long Si(Al) dual rotary target; blue: metallic mode, orange: transition mode, stabilized by an external gas control loop and green: reactive mode

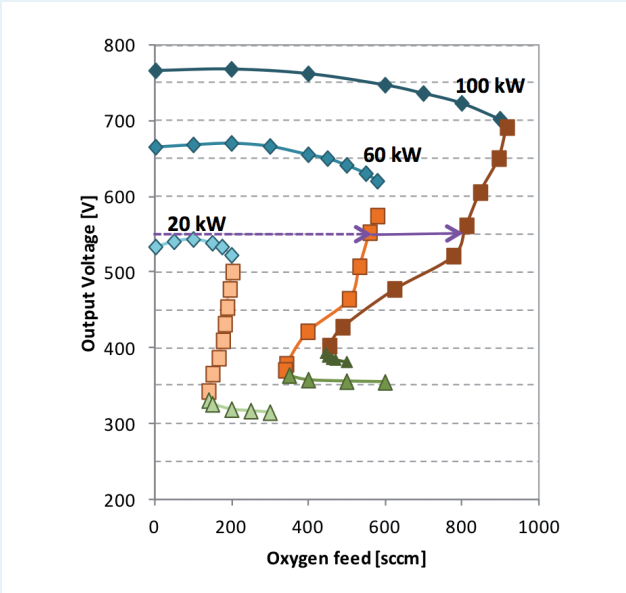

Figure 3: Generator output voltage during reactive sputtering. Target and operating modes as in Figure 2. The purple arrows line indicates the process at constant 550V.

The challenge: Stable transition mode operation

Ideally, the process state should be monitored and based on these data the oxygen supply or consumption should be controlled in such a way as to maintain the target in a condition between fully metallic and fully oxidized. This is the so-called transition mode shown in Figure 2 by orange symbols. For stable operation in this mode, the oxygen flow must be controlled by an external control loop.

In the case of silica and alumina, a suitable magnitude is the output voltage of the generator or target impedance. For other materials the optical plasma emission or the oxygen partial pressure may be used. The control by an external loop is well established in practical applications but puts high demands on the speed of gas flow regulation and distribution in the process chamber [3].

The alternative: Constant voltage operation

From the family of impedance curves at different input power levels, shown in Figure 3, it is clear that stable operation in the transition mode should also be possible by running the power supply as a constant voltage source: In this case the power increases with increasing oxygen flow, the value being determined by oxygen consumption and the target impedance. At constant 550V the power will be slightly above 20 kW from 0 to 200 sccm O_2 in the particular example shown here; it will reach 60 kW at 550 and 100 kW at 800 sccm O_2.

This method was suggested already 40 years ago [4], but it is only now being established in production coaters. This delay is related to some fundamental problems of the method:

(1) An ideal voltage source, reacting with infinite rate to load changes is not practical; there is some small delay due to the internal regulator bandwidth or at least through the inductance of the power feed cable.

(2) Oxygen coverage of the target surface can be very fast due to the long mean free path of gas molecules at process pressure (1 monolayer coverage in 100 ms at $2x10^{-3}$ mbar). This poses high demands on the reaction of the generator to load changes.

(3) At constant power and sputtering rate, the target impedance will decrease with target wear due to the increasing magnetic field. Consequently, the set voltage must be lowered gradually to maintain power and deposition rate constant.

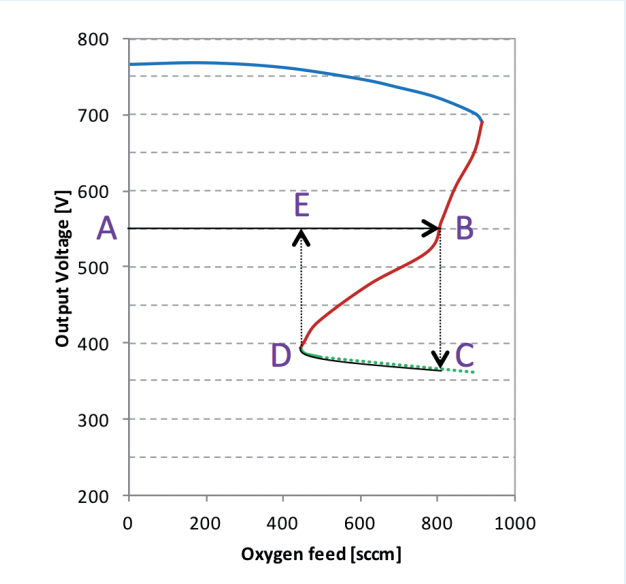

Figure 4: Operating points in voltage control mode.

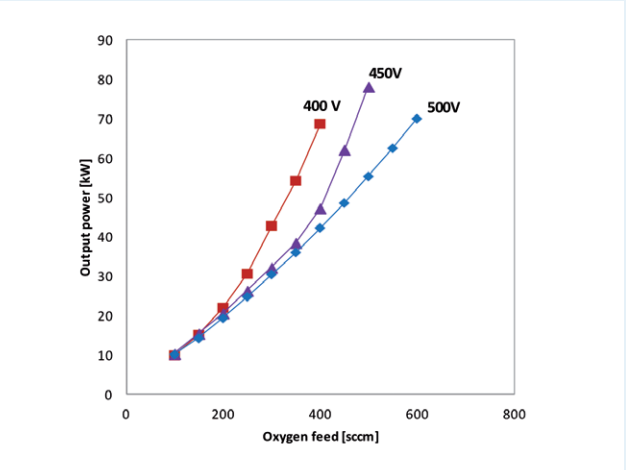

Figure 5: Output power increase with oxygen flow in voltage controlled operation mode. Target as in Figure 2.

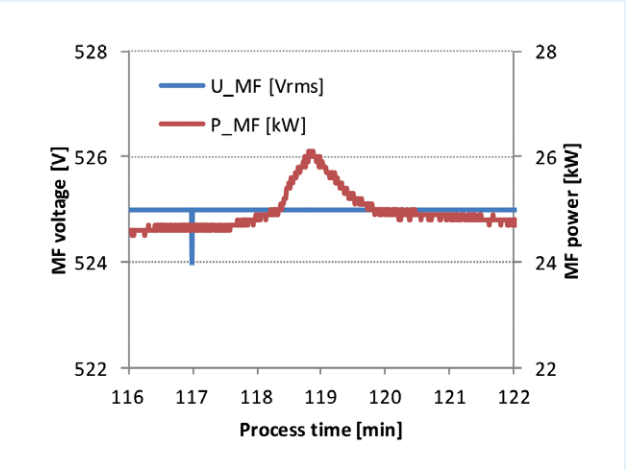

Figure 6: Power increase in voltage control mode during passing of a test substrate.

At a given voltage set point, the generator power may only increase to a certain maximum value, limited by the power handling capability of the target. This is indicated in Figure 4 by the arrow A-B. If the maximum power is reached, the target condition and voltage falls into the reactive mode along B-C at maximum generator power or current, whichever is limiting at the given target impedance. To move the process back into the transition mode, oxygen supply must be reduced briefly until the process state shifts along line C-D through the lower turning point back to the controlled transition mode in point E.

The solution: TruPlasma MF Series 7000 (G2)

Our new generation of MF power supplies TruPlasma MF Series 7000 (G2) was designed to meet the above criteria in the best possible way. An example of the dependence of output power on oxygen flow in voltage-control mode is shown in Figure 5. The new power supplies feature three independent controllers for MF power, MF voltage and MF current. At given settings, the target impedance determines which controller is active. Automatic switching between the P_{MF}, U_{MF} and I_{MF} controllers is available without overshoot or drop in output during change-over.

In principle, this offers the possibility to run the process along the line E-B in Figure 4. For this purpose, however, an additional control of the power (and thus the deposition rate) by the oxygen supply is required. Due to the proximity of a substrate or process gas entrainment, the target impedance may change suddenly. At constant O_2 flow and constant voltage this leads to power fluctuations, an example being shown in Figure 6. There is also the long-term impedance drift as the result of target wear.

When operating in the transition mode and in the event of a process shift to fully reactive (B-C in Figure 4), current or power control will continue without risk of shutdown due to the extreme impedance change.

Alternatively, the process may be run on the line C-D in Figure 4 at constant power. The highest deposition rate is then obtained at the turning point D. To keep the process from shifting to metallic (here approximately 750V) as the result of fluctuation in conditions, the new generators may be set to limit the voltage e.g. to 400V and thus keep the process near the turning point D. The power supply can safely switch between power and voltage control mode; with conventional technologies there was a risk of process instabilities.

Arcs may be detected within the half wave in which they occur and treatment may be started within less than 2 µs. The arc treatment

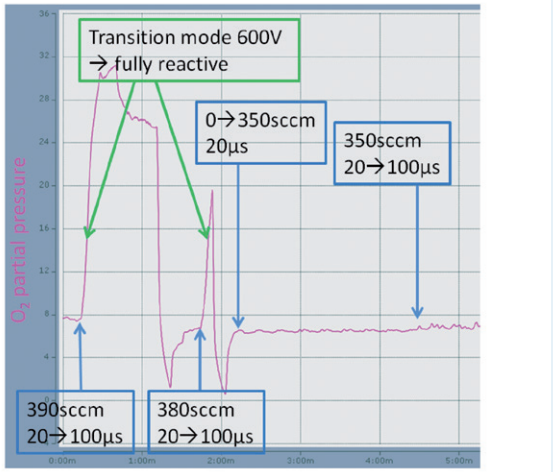

Figure 7: The temporal evolution of the O_2 partial pressure shows the process stability at 20 and 100us arc treatment time for different O_2 flows.

time may be selected very short at 20µs, such as to minimize average power loss at high arcing rates. The effect of the arc treatment time on process stability at about 100 arcs/sec. is shown in Figure 7 by the time dependence of the oxygen partial pressure. Voltage-controlled operation at 600V was possible with 20µs treatment time here at 390 and 380sccm O_2. But increasing the treatment time to 100µs led to a process shift to fully reactive and thus to a strong increase of the O_2 partial pressure. The process was brought back to the transition mode here by briefly interrupting the O_2 flow. With 350sccm O_2, the process remained in the transition mode, but it was noticeably less stable. The improved arcing tolerance also provides a key to better target utilization.

In conclusion, the new power supply design is a step forward towards a wider accessible process window in reactive sputtering.

Light and transparent:
TRUMPF Hüttinger Headquarters in Freiburg / Germany

Written by

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[2] For a review see chapter 4 in „Reactive Sputter Deposition“, D. Depla, S. Mahieu (eds.) Springer 2008
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