New Features of DC Power Supplies for TCO Magnetron Sputtering

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Abstract
Transparent Conductive Oxides are of great importance for thin film solar cell application. All major thin film solar cell types as a-Si/µc-Si, CdTe and Cl(G)S use TCO materials, most often ZnO:Al, for the transparent contact layer. Magnetron sputter processes are widely used for the deposition. As AZO sputter processes show a very high arcing rate pulsed DC power processes have been needed in the past. A new DC power supply family has been developed with the goal to replace these expensive pulsed DC processes by standard DC magnetron sputtering. The most important feature of this power supply is a very fast and advanced arc management. After detecting an arc a positive voltage is applied to the cable between power supply and cathode. This compensates the stored energy of the cable and reduces the energy supplied into the arc after power switch off. By that way residual arc energies significantly less than 1 mJ/kW are enabled. Because of the very short process interruption stable processes with the in production reached arcing rates of 6000 arcs/s and higher become possible. Measurements using a 60kW power supply have shown very stable process conditions over a long time for planar and tube AZO targets. Transmission and resistivity of layers deposited with DC have been measured at a lab coating system and compared with pulsed DC deposited layers. Comparison shows similar results for both technologies. The fast arc management with adaptable parameters results in superior film quality, and homogeneity of the deposited film. It could be demonstrated that pulsed power can be replaced without any disadvantage.

Introduction
Transparent Conductive Oxides (TCO) are of great importance for a-Si/µc-Si, CdTe and Cl(G)S type thin film solar cells. For all of this cells TCO materials are needed for the transparent contact layer. The most often used material is ZnO:Al (AZO). The principal layer stack design of these thin film solar cells is shown as example for the Cl(G)S type cells in fig. 1 [1,2]. Most of the layers are deposited using magnetron sputtering. These are the transparent contact layer (AZO), the heterojunction performance enhancement layer (i-ZnO), the metallic back contact layer (Mo) or components of the compound semiconductor layer itself as Cu and In. While Mo, Cu and In are standard DC sputtering processes for ZnO:Al and i-ZnO pulsed DC often has been used in the past because of the high arcing rates of these materials. The
new DC power supply family has been developed with the goal to replace these expensive pulsed DC processes by standard DC.

Figure 1: CI(G)S type thin film solar cell layer stack.

Fig. 2 shows the principle set up of the magnetron sputtering deposition method. The target of the magnetron is connected to a high, negative voltage. By that way the plasma is ignited in front of the target, locally fixed by the magnet array. Positive Ar ions are generated in the plasma and accelerated towards the target and remove target material by collision. A thin, uniform and compact layer with the desired structure and composition is build up on the substrate.

Figure 2: Set up for magnetron sputtering.

**DC Power Supplies**
The DC power supply is designed for powering sputtering cathodes. The most important features of the power supply are a high efficient switched-mode power
conversion technique, up to 800 V operating output voltage, full output power capability at output voltage down to 400V, a fast arc switch off and recovery, an extremely low arc energy and a wide variety of user adjustable parameters. All units are microprocessor controlled. The most important feature is the highly advanced arc management. Localized electric discharges, often called arcs, can occur inside the vacuum chamber. This arcs lead to defects and inhomogeneities in the deposited layer and can create holes in the target material. For that reason arcs should be extinguished as fast as possible. The DC power supply is equipped with 3 different arc detection criteria to ensure fast response to an arc occurrence. One of these criteria is a current based detector which reacts when the output current $I_{out}$ exceeds a user defined current threshold value $I_x$ (fig. 3). The detection time depends on the chosen value for the threshold and is typically about 300ns. The switch off time is about 1.5µs. The break time and ramp time can be chosen in a wide value range between 0ms and 80ms or 100ms respectively.

![Figure 3: Current based arc detection sequence.](image)

The second detection criterion is the voltage drop during the arc occurrence. The voltage based detector is armed when the output voltage exceeds a user defined threshold $A$ and triggers when the voltage drops below a user defined threshold $B$.

The third detection method is a combined voltage and current based detector which reacts when the output voltage is lower than the user defined voltage threshold while the current is higher than the user defined current threshold. A more detailed description can be found in [3].

Additional to this very fast arc detection the so called CompensateLine was implemented in the power supply. This is a positive voltage applied to the magnetron power cable after arc detection and power switch off. Fig. 4 shows the principle of this feature. During standard operation a capacitor $C$ is charged up. In the case of an arc event the fast switch $SS$ is opened and the positive potential of the capacitor plate is applied to the cable. The in the cable between power supply and cathode stored inductance energy can be calculated by $E = (LI^2)/2$. With an estimated value for the cable inductance of $L = 1µH$ per meter the inductance energy for a 10m long cable and a process current of $I = 100A$ amounts for example to 50mJ.
By applying the positive voltage the negative potential of the cable is reduced very fast. This results in a further decrease of the residual arc energy which is delivered to the cathode after arc detection.

The improved arc detection in combination with the CompensateLine feature realizes a very fast power switch off with residual arc energy significantly lower than 1 mJ/kW. DC power supplies of this type are available from 2 to 120 kW maximum output power.

DC Magnetron Sputtering Deposited ZnO:Al

The power supply performance has been investigated for AZO. Doping of ZnO leads to an highly n-type conductive material [4,5]. AZO layers have been prepared and measured at the inline sputter plant ILA 750 at the Fraunhofer FEP. The planar AZO magnetron target has a size of 750x120mm. The DC power supply was connected via a 12m cable with the magnetron. Standard pressure of the process was set to $3 \times 10^{-3}$ mbar responding to an argon flow of 200sccm. Layers have been deposited on glass substrate, which has been pre-cleaned using a RF plasma process. Layers have been deposited at room temperature. Some of the samples have been annealed after AZO deposition in vacuum for 15min at 350°C. Oscilloscope measurements of arc events have been performed for the CompensateLine (CL) option of the DC power supply switched on or off.

The current characteristics of an arc event occurring during the AZO magnetron sputtering process with and without CL is shown in fig. 5.

During the arc event the current rises from the process value of 10A to about 30A. After about 2µs the power is switched off and the current decreases. After another 7µs the current decreases to about zero ampere. With CL the current drops much faster after power switch off. The zero ampere level is reached in less than 1µs. This reduces the energy delivered into the arc significantly to less than 1mJ/kW.
Transmission has been measured for 460nm thick AZO layers deposited on glass. For comparison pulsed DC deposited layers have been prepared. The unipolar pulsing was done at a frequency of 50kHz and with a duty factor of 75%. As shown in Fig. 6 there is no difference in transmission spectra for the two processes. Both samples have been annealed in vacuum at 350°C for 15min. After this treatment transmission at lower wavelength is slightly increasing whereas for the higher wavelength the transmission is decreased. Again there is no difference between the DC and pulsed DC process.
Comparison of the two deposition processes has also been carried out for the layer resistivity as shown in fig. 7. The resistivity of the 460nm thick DC sputter deposited AZO was measured for different additional oxygen flow (triangles). The lowest resistivity values have been achieved without any additional oxygen. Samples prepared with the pulsed DC process (squares) show slightly worse resistivity values.

Figure 7: Layer resistivity of 460nm AZO on glass for different O₂ process gas flow.

Conclusion
A new DC power supply family has been developed with the goal to replace the expensive pulsed DC processes by standard DC processes. The most important feature of this power supply is a very fast and advanced arc management. This enables processes with residual arc energies significantly less than 1 mJ/kW. An additional benefit of the arc management is that as a result of the very short process interruption stable processes with in production reached arcing rates of 6000 arcs/s and higher become possible. Transmission and resistivity of AZO layers deposited with DC have been measured at a lab coating system and compared with pulsed DC deposited layers. Comparison shows similar or even better results for DC sputter deposition. It could be demonstrated that pulsed power can be replaced without any disadvantage.

References

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