Empowering thin-film cells: how DC and RF generators impact high-quality coatings of thin-film solar cells

Dirk Ochs, HÜTTINGER Elektronik GmbH + Co KG, Freiburg, Germany

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ABSTRACT

The rapidly-growing photovoltaic market has placed a strong demand on manufacturers to decrease solar cell production costs. For thin-film solar cells, this can be achieved by increasing substrate sizes to achieve a better productivity and by adding more advanced layer stack systems to enhance the solar cell's efficiency. Nearly all required layers of the prominent thin-film-based solar cell types (a-Si/µc-Si, CdTe and CI(G)S) can be deposited by using plasma processes. On the one hand, plasma-enhanced chemical vapor deposition (PECVD) is used for the deposition of a-Si and µc-Si layers. On the other hand, magnetron sputtering is used for coating with transparent conductive oxides as ITO (indium tin oxide) and ZAO (aluminium-doped zinc oxide), metallic back contact layers such as Ti, Al and Mo, or components of the compound semiconductor layers such as Cu and In. Magnetron sputter processes use direct current (DC) or pulsed DC, whereas radio frequency (RF) power is used for PECVD processes. Of utmost importance to get a reliable, high-efficiency solar cell is a good uniformity of the deposited layers and the need for the layer to be defect-free. Defects such as particles and splashes are created inside the plasma when an unwanted local discharge – a so-called arc – occurs. This arc can be eliminated by switching off the power supply. The faster this is done, and the less energy that is delivered into the arc, the smaller and more insignificant the defect creation will be. For this reason, as well as for precise control of electrical power, advanced, fast-reacting arc management is very important to attain high-quality solar cell coatings.

Introduction

Solar cells can be divided into two main groups. While wafer-based solar cells are the most commonly-produced type, thin-film solar cells will increase in popularity and importance over the next few years. The most prominent thin-film solar cell types are a-Si/µc-Si [1,2], CI(G)S [3] or CdTe [4]. The principal layer stack design of these cells is shown in Figure 1, while Table 1 shows the different materials used for these layers, most of which are deposited using plasma-based methods. Deposition of these layers can be divided into two main groups: PECVD deposition for Si-based layers, usually using RF power, and magnetron sputtering for coating with transparent conductive oxides (TCO). Magnetron sputtering processes mainly use DC power.

Transparent contact layer	AZO, ITO
Active layer	a-Si, µc-Si, CdS/CdTe, CdS/CIS
Metallic contact layer	Mo, Al, Ag
Substrate	Glass, polymer foil, metal strip

Table 1. Thin-film solar cell materials.

All DC and RF power supplies used for solar cell applications need a high precision process control and a supreme arc management with adaptable parameters to provide minimal disturbances in the plasma process and to obtain optimized results in terms of film quality, homogeneity and uniformity over the whole substrate. The principal function of a power supply is the power conversion from mains into different voltage and frequency levels, and the isolation between mains and load and the dynamic control of the process power. In particular, the dynamic range of the plasma impedance has to be considered in the design to cover the three states of the plasma and the transition between them: insulating gas, ignition, plasma, arc and arc quenching.

DC coating processes

Magnetron sputtering is used for the majority of thin-film solar cell layers. Figure 2 shows the principle set-up for

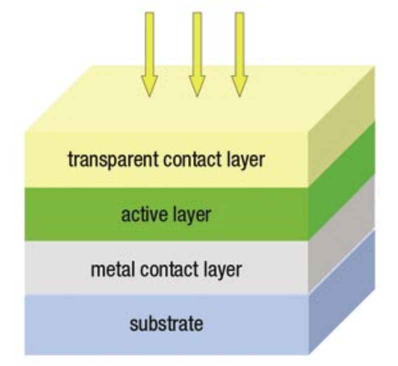

Figure 1. Principle design of thin-film solar cell layer stack.

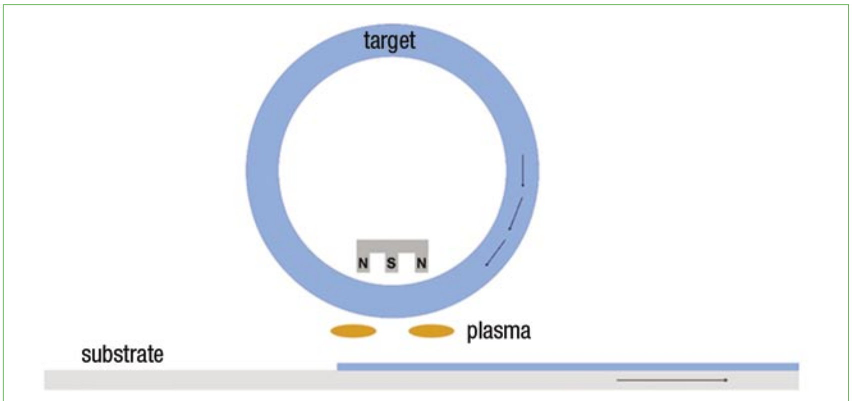

Figure 2. Principle set-up for rotatable magnetron sputtering.

Detection time	< 300ns
Switch off time	Ca. 1.5 µs
Break time	0-80ms
Ramp time	0-100ms

Table 2. Values noted during current-b detection sequence (see Figure

rotatable magnetron sputtering. The rotatable tube target of the magnetron is connected to a high negative voltage. In this way, the plasma is ignited in front of the target locally fixed by the magnet array. The 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 built up on the substrate.

For all of these layers, a good thickness homogeneity of the deposited layers at high deposition rates is very important. The DC power supply (MP family) is designed for powering sputtering cathodes. The most important features of the power supply are a high-efficiency switched-mode power conversion technique, an operating output voltage up to 800V, 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 of the aforementioned features is the highly advanced arc management. Electric arcs that can occur inside the vacuum chamber may negatively affect the treated surface and for that reason arcs should be extinguished as quickly as possible. The arc detection system is equipped with three different arc detection criteria to ensure fast response to an arc occurrence. One of these criteria is a current-based detector that reacts when the output current I_{out} exceeds a user-defined current threshold value I_x (see Figure 3).

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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

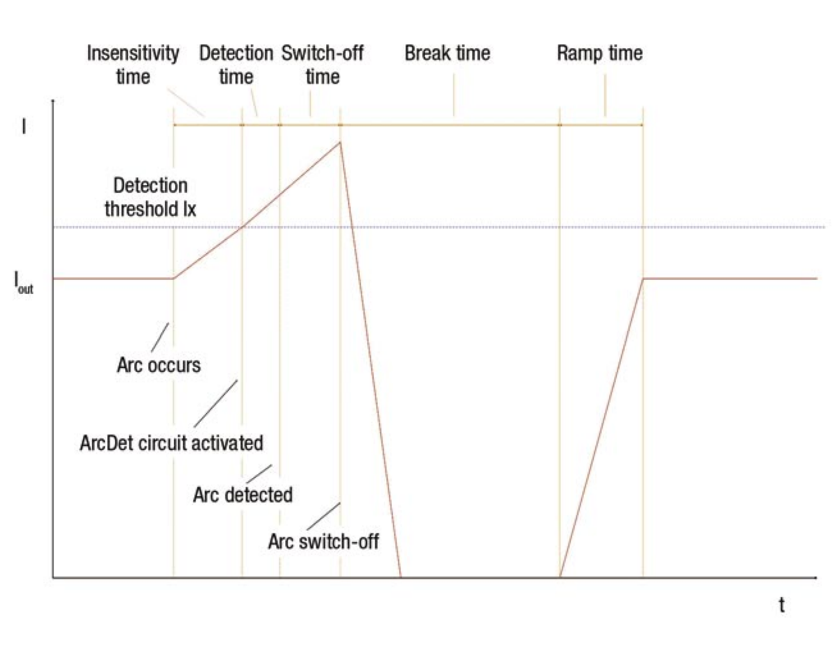

Figure 3. Current-based arc detection sequence.

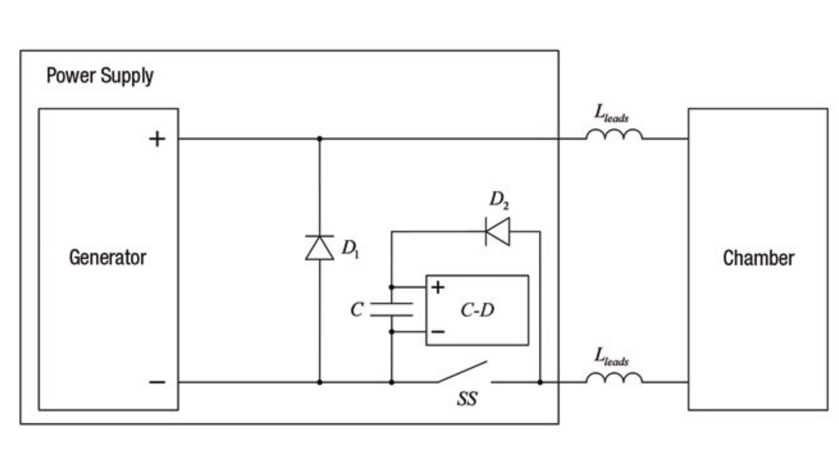

Figure 4. Principle of the cable length compensation.

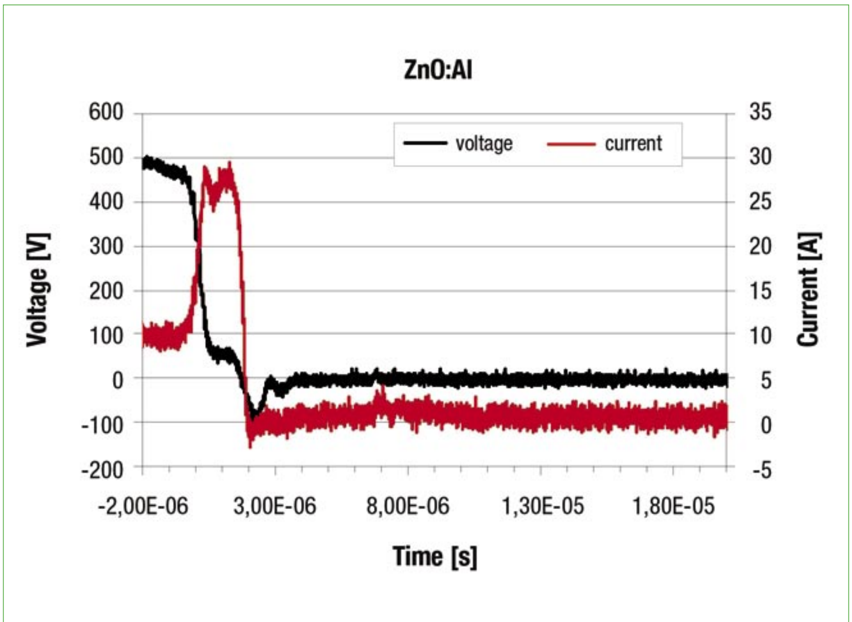

Figure 5. Current and voltage during an arc event using CLC.

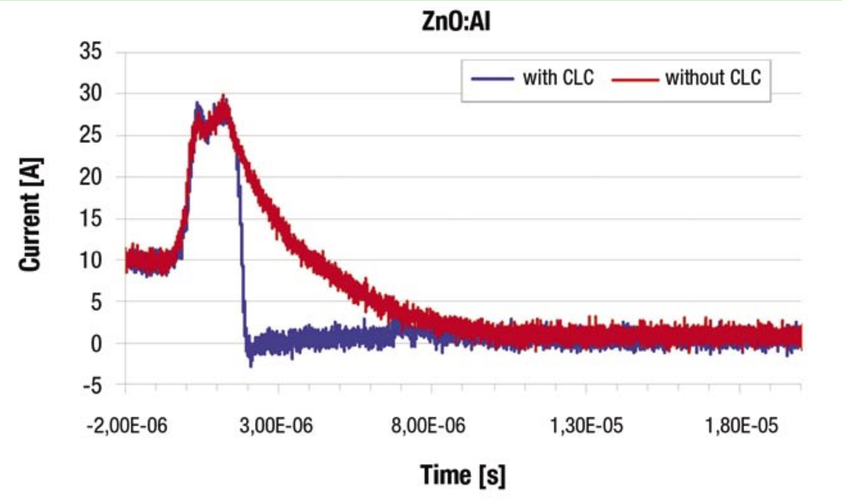

Figure 6. Current during an arc event with and without CLC.

voltage is lower than the user-defined voltage threshold and the current is higher than the user-defined current threshold. Table 2 shows the typical values for the time windows described in Figure 3.

In addition to this very fast arc detection, a so-called cable length compensation was implemented in the power supply. This is a positive voltage applied to the magnetron power cable after arc detection and power switch-off. Figure 4 shows the principle of this feature.

By applying the positive voltage, the negative potential of the cable is very quickly reduced. This results in a further decrease of the residual arc energy which is delivered to the cathode after arc detection. Figure 5 shows the current and voltage of an arc event at a ZnO:Al (AZO) target using a power supply with CLC. For comparison purposes, the current during the arc event is shown for a power supply with and without cable length compensation (Figure 6). The faster decrease of the current resulting from the CLC is clearly visible. This reduces the energy delivered into the arc significantly.

The improved arc management in combination with the cable length compensation feature realizes a very fast power switch-off with a residual arc energy significantly lower than 1 mJ/kW. DC power supplies of this type are available from 1 to 240kW maximum output power.

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RF coating processes

In additon to the DC power supplies, RF power is needed, especially in the case of Si layer deposition. PECVD deposition of layers as a-Si and µc-Si is performed using RF excited plasma processes [7, 8]. The typical RF operating frequency is 13.56MHz, but higher frequencies are also used. In order to have a cost-effective design for a high-power RF generator in the power range up to 50kW, an oscillator-amplifier concept has been chosen with a solid-state driver in combination with a tube type end stage amplifier (see Figure 7).

Starting from 1µW, the signal is modulated for power control and pulsing

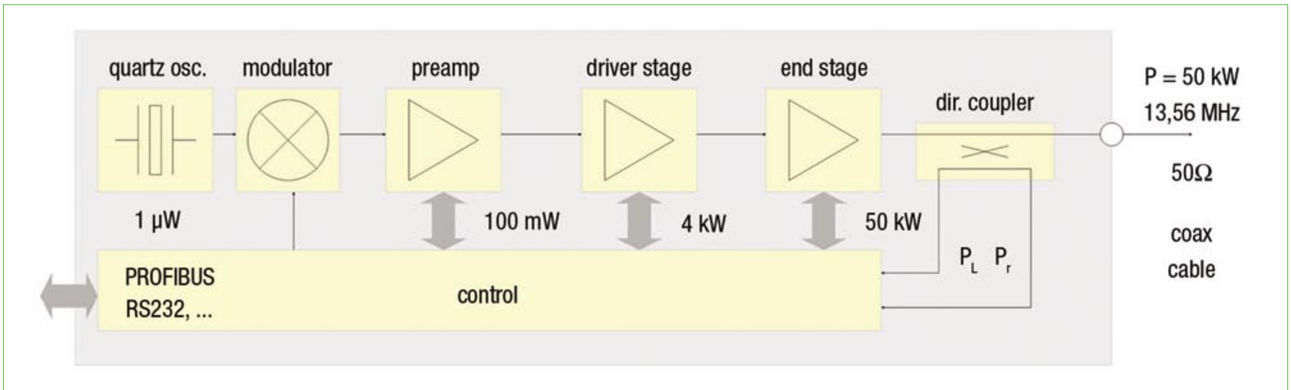

Figure 7. Principle design of the RF power supply.

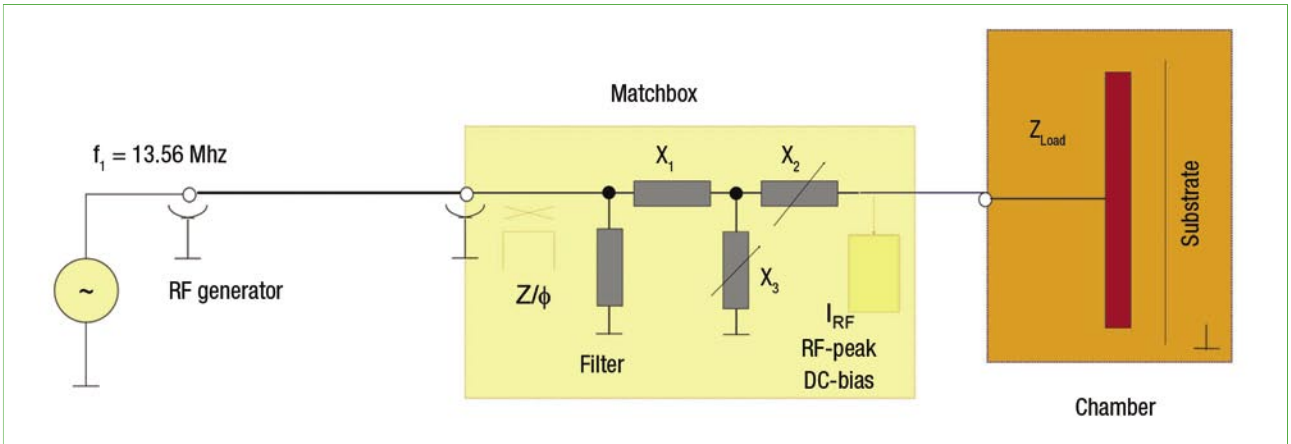

Figure 8. Principle of an impedance transformation network.

functionality before it reaches the chain of amplifiers where the power of the modulated signal is increased in the pre-amplifier to a level of 100mW and in the driver stage to a level of 4kW. Finally, the robust tube type end stage creates the output power level of up to 50kW. The output power that is delivered into the 50Ω coaxial cable is controlled and the incident and reflected part is measured by the directional coupler.

The impedance of the cathode varies with the process in the range of 1-5Ω with a strong capacitive part. In contrast, the output impedance of the generator has 50Ω. In order to deliver the maximum output power of the generator to the chamber, an impedance transformation network is required.

The impedance of the cathode is matched to the 50Ω via a network of three elements as shown in Figure 8. To compensate the varying impedance of the process, two of the three elements are variable by motor-controlled vacuum capacitors. The resulting impedance of the matchbox and process parameters – such as the RF peak voltage and the DC bias voltage – are measured and delivered to the controller inside the matchbox. These signals are also transferred to the generator which acts as a system controller.

By these means, even critical processes can be ignited and stabilized for long cycle times. Depending on the needs of the process, the system can operate in constant wave mode as well as in pulsed mode.

Summary

For wafer-based and thin-film solar cell applications, high power DC and RF power supplies are available that meet the specific process-related technical and economical requirements. These requirements are a high precision process control, and a supreme arc management with adaptable parameters to provide minimal disturbances in the plasma process and to obtain optimized results in terms of film quality, homogeneity and uniformity over the whole substrate. The better the quality of the deposited layers, the higher the efficiency of the solar cell.

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About the Author

Dirk Ochs joined HÜTTINGER Elektronik GmbH + Co KG in 2005 as Senior Application Engineer. He is responsible for all application-related items of the HÜTTINGER power supplies in the field of plasma deposition, etching and modification processes. He studied physics at the Justus Liebig University in Giessen and received his Ph.D. in surface science at the Technical University Clausthal-Zellerfeld in 1998. Prior to joining HÜTTINGER, he worked for seven years in the development departments of vacuum coating equipment manufacturers Oerlikon and Singulus consecutively, focusing on the development of new plasma coating and etching equipment as well as the development of related processes.

Enquiries

Dr. Dirk Ochs
Tel: +49 (0) 761 8971 2165
Fax: +49 (0) 761 8971 1150
Email: dirk.ochs@de.huettinger.com