Influence of the Excitation Frequency Increase up to 140 MHz on the VHF-PECVD Technology

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Abstract: The plasma enhanced chemical vapor deposition process with a linear plasma source and the frequency range up to 140 MHz developed by Dresden University of Technology and FAP GmbH Dresden enables a fabrication of thin film silicon layers at very high deposition rates. However, an increase of the plasma frequency reduces the electromagnetic wavelength. Therefore, the electric field distribution is simulated to examine an influence of electrical properties and the deposition system geometry on the homogeneity of deposited layers. A detailed electrical model of the linear plasma source for 3D simulation is developed. Additionally, the simulation results are used to create an electrical lumped model of the structure to investigate the influence of the excitation frequency on the structure impedance.

Keywords: CCP, PECVD, VHF

1. Introduction

The plasma enhanced chemical vapor deposition technology (PECVD) is one of the most important deposition techniques for the amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon thin film and solar cell fabrication. The deposition process is based on the surface reactions at the interface between the substrate and the reactive plasma phase. The gas molecules are introduced into the discharge area, and due to electron impact reactions are broken down into reactive particles in the dissociation process. These precursors are able to form a chemical binding on the substrate surface generating a new layer of solid material [1].

The process developed by Dresden University of Technology and FAP GmbH Dresden enables the deposition of homogenous a-Si:H and μc-Si:H layers on large area substrates at high deposition rates using linear plasma sources at very high excitation frequencies up to 140 MHz. In the VHF range the electric field wavelength inside of the PECVD reactor is comparable with the electrode dimensions (500x100mm) which causes formation of standing waves inside the deposition chamber. Therefore the electric field distribution was simulated to examine an influence of the electrical properties and the deposition system geometry on the homogeneity of the deposited layers.

2. Linear Plasma Source

The linear plasma source is a substantial part of an inline deposition system [2-3] (Figure 1).

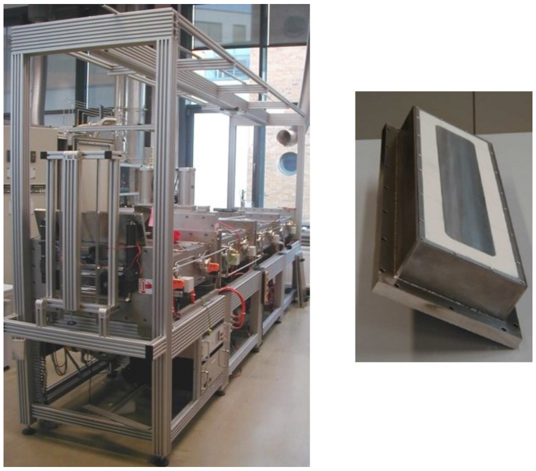

Figure 1. Left: VHF PECVD deposition system, right: linear plasma source.

A schematic view of the whole system is shown in Figure 2. It consists of three interconnected modules, for the deposition of p-, i-, n- layers respectively.

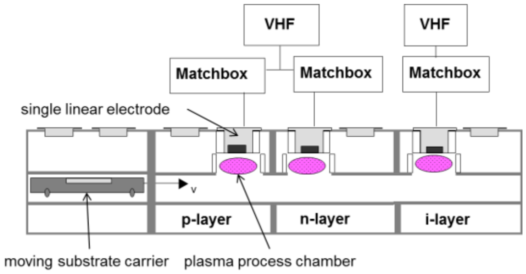

Figure 2. Schematic view of the VHF-inline deposition system.

This work is focused on the modeling of the i-chamber, where the frequencies up to 140 MHz are used. The substrate is located on the grounded carrier, which moves horizontally inside the tunnel during the process. The VHF Electrode is placed above the substrate forming the capacitive coupled plasma (CCP) geometry.

In a previous work [4] a simplified model of the linear plasma source and the substrate carrier as a two electrode system and in a first approach vacuum in between has been used.

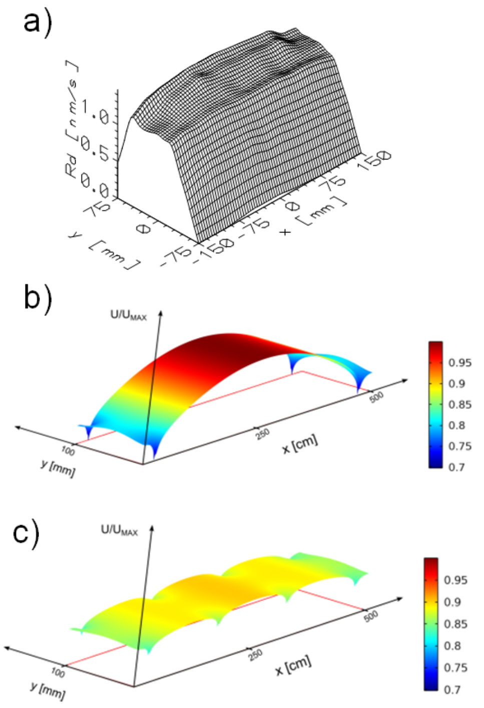

Figure 3. Deposition rate profile (a) compared with electrical field distribution at 140 MHz: (b) a simple power coupling solution, (c) an optimized power coupling solution.

The electric field between the electrodes shows (Figure 3 b) the formation of standing waves which also corresponded with measured deposition rate profiles of intrinsic amorphous silicon layers (Figure 3 a). Additional to compensate the standing wave effect an extended power coupling solution has been designed and has been modeled (Figure 3 c).

This was the motivation to build a more detailed electrical model which better corresponds to the linear plasma source. Additionally, the simulation results were used to create an electrical lumped model of the structure to investigate the influence of the high excitation frequency on structure impedance.

2.1 Geometry of the linear plasma source

The geometry of the linear plasma source and deposition chamber was created using AutoCAD® Software (Figure 4).

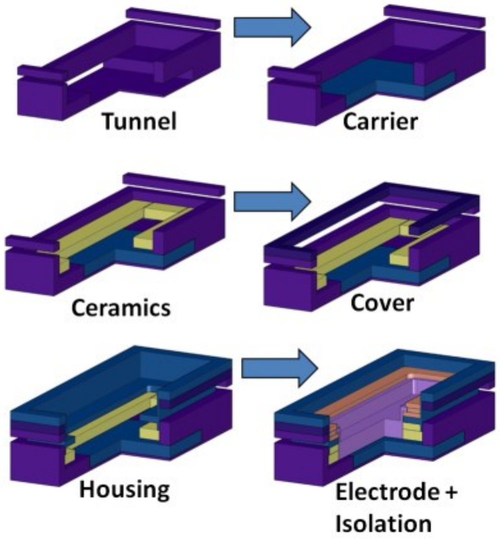

Figure 4. Geometry of the linear plasma source

The grounded carrier is located inside the tunnel with the 1 mm distance to the tunnel walls. The VHF electrode is placed 9 mm above the carrier. The other chamber elements are grounded. Additionally, the ceramics fills the empty area between the electrode and tunnel walls and ensures the electrical isolation.

2.2 COMSOL - geometry simplification

Using the LiveLink™ interface the geometry was imported into the COMSOL software. Considering the physics of the electric field propagation the structural model of the deposition chamber had to be simplified. Therefore an engineering model was developed (Figure 5). Due to the fact that the structure has two symmetry surfaces (longitudinal and transversal) only one quarter of the whole structure was taken under consideration. Next, the metallic elements were simplified. According to the following equation the skin length of aluminum in the VHF range (up to 140 MHz) is smaller than the size of the conducting elements:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

δ – skin depth [m]
ω – angular frequency [rad/s]
σ – resistivity [Ω·m]
μ – absolute magnetic permeability [H/m]

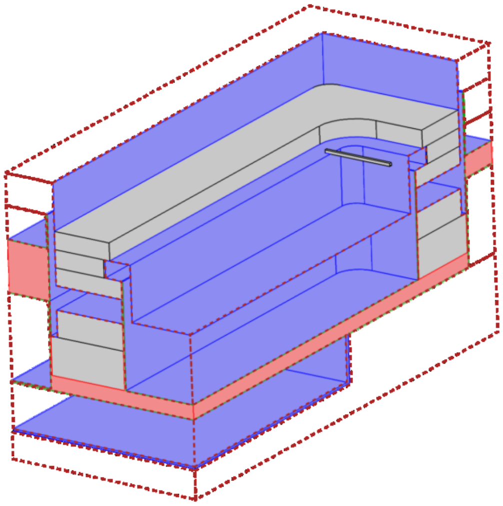

Figure 5. COMSOL structure simplification

Under these conditions all conductive volumes were reduced to conductive surfaces. Additionally for the simulations of the impedance model the coupling feeds were defined as coax connection (Figure 6).

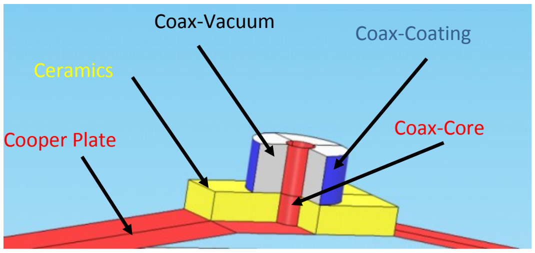

Figure 6. Coax port with the connection geometry

2.3 Mathematical model

The electromagnetic analysis was performed using the Maxwell`s equations under certain boundary conditions. The Maxwell`s integral and differential equations are used to describe the basic electromagnetic parameters:

- Electric Field **E**
- Electric Flux Density **D**
- Magnetic Field **H**
- Magnetic Flux Density **B**
- Electric Current Density **J**
- Electric Charge Density **ρ**

The Maxwell`s equations describe how the electric and magnetic fields propagate and interact and how they are influenced by other objects with the following formulas:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial \boldsymbol{t}}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}}$$

$$\nabla \cdot \boldsymbol{D} = \rho$$
$$\nabla \cdot \boldsymbol{B} = 0$$

The first two are known as Ampère`s law and Faraday`s law respectively. The 3rd and 4th are called Gauss` laws.

The other important relation used in this study is the continuity equation:

$$\nabla \cdot \boldsymbol{J} = -\frac{\partial \rho}{\partial t}$$

2.4 Physical model

Next, the material parameters and boundary conditions were defined. The symmetry surfaces were defined as perfect magnetic conductors:

$$\hat{n} \times \overline{H} = 0$$

$\overline{H}$ – magnetic field [H/m]
$\hat{n}$ – normal to the boundary surface

The grounded boundaries were described as perfect electric conductors (PEC). The VHF electrode surface and the bulk isolation elements had the following parameters:

Table 1: Electrical parameters

Material	Conductivity [S/m]	Permea-bility	Permi-ttivity
Aluminum	$3.03*10^7$	1	1
Ceramics	0	1	9.6
PEEK	0	1	3.3
Vacuum	0	1	1

Additionally, the discharge area was filled with perfect vacuum instead of plasma gases. This creates a simplified physical model, which neglects all effects caused by the presence of plasma.

The input electromagnetic field was excited using a voltage lumped port. The 1 V source with an inner resistance of 50 Ω was applied as an electrical feed. The dimensions of the feed geometry are smaller than one-tenth of the electromagnetic wavelength. Therefore, the electrical field can be calculated using the following equation [5]:

$$V = \int_{h} (E \cdot a_h) dl$$

V – voltage [V]
h – distance between the metallic contacts [m]
l – length of the metallic edges [m]
a_h = h · l - contact surface [m^2]

3. Results

The electrical field distribution on the surface 0.5 mm above the grounded carrier was analyzed (Figure 7 and Figure 8). The study were performed over the whole electrode area (100 x 500 mm^2). In the HF frequency range up to 80 MHz no significant wave effects were observed (Figure 7) since the field below the HF electrode area is flat.

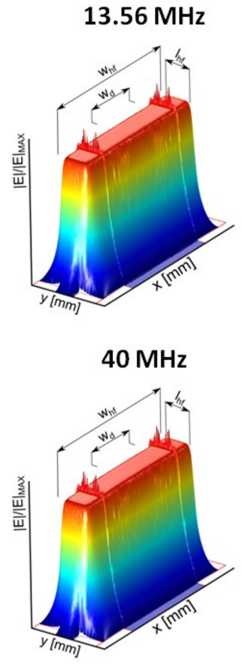

Figure 7. Electrical field distributions in vacuum in the HF range, where the area of the electrode (w_{hf} x l_{hf}) equals 100 x 500 m^2 with the deposition area (w_d x l_{hf}) of 100 x 300 m^2.

The simulations in the range above 80 MHz were compared with measured deposition rate profiles of hydrogenated amorphous silicon.

During the layer deposition the substrate carrier was located in the centre beneath the powered electrode. The local film thicknesses of intrinsic amorphous silicon in the deposition area of 100 x 300 mm^2 was converted into 3D deposition rate profiles, to get a better impression of the thin film uniformity. The investigation of the plasma homogeneity was performed at the frequencies of 81.36, 120 and 140 MHz (Figure 8 left).

With increasing excitation frequency (from 81.36 to 140 MHz) the standing waves had more impact on the electrical field homogeneity (Figure 8 right) which corresponded to the changes in the deposition profile inside the 300 mm wide deposition area (w_d).

Observed electric field peaks at the edges of the carrier correspond to powder formation during the PECVD process. The shape of the peaks is highly irregular due to limited computation mesh density.

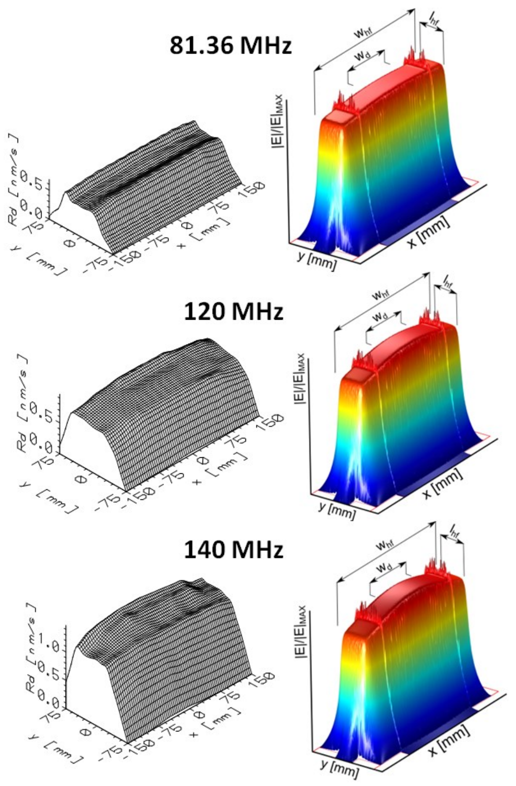

Figure 8. Deposition rate profiles (left) compared to electrical field distribution (right) in vacuum in the VHF range.

To validate the electrical model of the plasma source impedance measurements of the real structure were performed and compared with the modeling results. The impedance model requires simulation of the electromagnetic field distribution inside the whole 3D plasma source. Therefore, this method also validates the whole electromagnetic model of the PECVD reactor.

During the measurement the HF source was connected with the plasma source through the detector (Figure 9). The voltage, current and the phase shift of the input and reflected signal were measured. The measured impedance (Z_c) was related to the electrode and connection elements to the detector (Figure 9 above). To evaluate the impedance of the electrode surface the impedance of the connection feeds (Z_0) have to be measured (Figure 9 below) and subtracted from the previous parameter (Z_c).

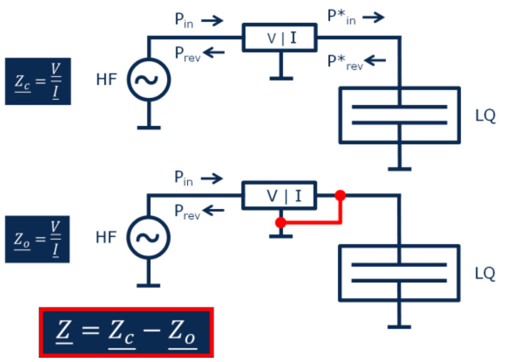

Figure 9. Impedance measurement setup: electrode and feed impedance (above); impedance of connection elements (below).

In Figure 10 a comparison between the simulation and the measurement of the real structure are shown. The impedance simulation results show 5% deviation from measured values. For the reactance (X value) the only noticeable deviation occurs at very high frequencies above 140 MHz (Figure 10 above).

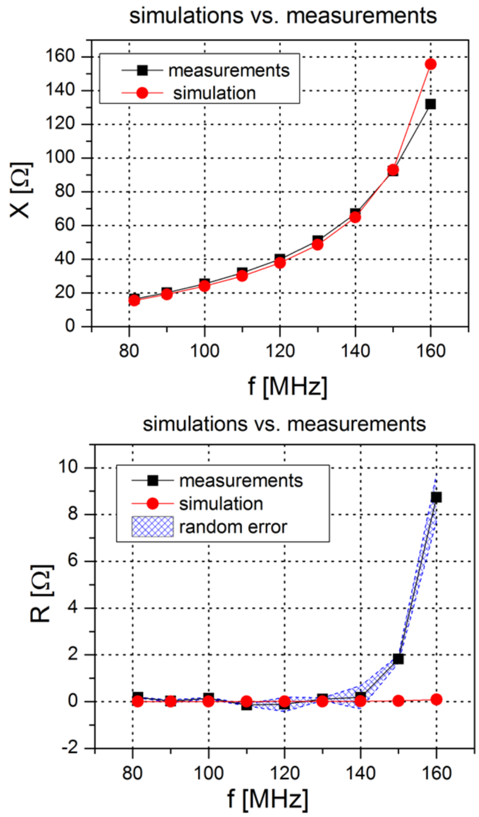

Figure 10. Measured and simulated reactance (above) impedance (below) of the linear plasma source

The real part of the impedance (R) should be around zero, hence the resistance of metallic elements is low. The simulation matches the theory at this point and should be treated as a reference (Figure 10 below). The last two impedance values were obtained around the limiting frequency of the detecting system, which explains the most significant difference between simulations and measurements at these frequencies.

3. Conclusions

This study shows that detailed electrical models which neglects all effects caused by the presence of plasma give important information about homogeneity of deposited layers in a complex deposition system. Furthermore, observed electric field peaks at the edges of the carrier correspond to powder formation during the PECVD process. Comparison of the electrical properties of the developed model and the real object confirmed the possibility to model highly complicated 3D structures.

Furthermore, the lumped model of the structure can be used to validate the simulation process as well as to improve the electrical matching of the system.

This model can be further developed by introducing plasma physics modeling in the deposition area.

4. References

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