Impedance Spectroscopy of Al/a-SiC/c-Si(n)/Al Solar Heterojunction Structure

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Abstract — **Amorphous silicon carbide a-SiC is compound with tetrahedrally coordinated structure. It may be used in various branches of electrotechnical production. The influence of elevated temperature treatment on the properties of prepared Al/a-SiC/c-Si(n)/Al heterojunction structure was studied by complex impedance spectroscopy in the dark. AC equivalent circuit was obtained by fitting of biased impedance dependences and the electronic components were used to describe the electronic transport properties of prepared structures and clarification of the impact of elevated temperature treatment.**

Keywords — Photovoltaics, PECVD, AC characterization, impedance spectroscopy.

I. Introduction

The structures of the amorphous silicon carbide a-SiC (or more precisely a-$Si_{1-x}C_x$) and its hydrogenated form (a-$Si_{1-x}C_x$:H) can be prepared by various techniques. Plasma enhanced chemical vapor deposition techniques [1, 2], reactive sputtering [3], radiofrequency sputtering [4], and also electron cyclotron resonance (ECR) supported vapor deposition CVD [5] are often used.

Electrical, optical and structural properties of prepared thin films depend on the method of deposition and the deposition parameters (radio frequency power in the reactor, the reactor chamber pressure and substrate temperature) settings. Used gaseous precursors and their flow ratios also significantly influence the resulting properties of the structures [6]. The existence of different types of structural defects is a well-known feature of silicon and carbon amorphous compounds. Disordered structure which is related to the presence of different recombination centers is problematic for some electronic applications, especially with respect to the reliability and efficiency of such devices. Optimization of technology in order to improve the quality of interfaces and layer quality is therefore still a major challenge for research and development [7, 8, 9, 10].

The presented experimental results were obtained on a-SiC thin films (layers were part of heterostructures), which were prepared by PECVD method. Thin films of a-SiC were deposited on a heated substrate in a PECVD reactor with a capacity coupled plasma. Mixture of gases $SiH_4 + CH_4 + H_2 + B_2H_6$ was used as a basic precursor. Argon was fed to reactor to stabilize the plasma. Hydrogen in the gas mixture was introduced into the reactor in order to passivate unsaturated bonds in the forming amorphous structure.

II. Photovoltaic Applications

Amorphous silicon carbide is used in photovoltaics mainly due to the relatively simple possibility to control the optical and electrical properties. Amorphous SiC is preferably applicable as "optical window" (window layer) in the construction of tandem solar cells due to the greater width of the band gap compared to pure amorphous silicon (a-Si). Amorphous SiC is also a perspective material for the third generation of PV cells [11, 12], which uses the concept of matrix quantum wells (quantum dots matrix). Second generation of PV cells consisting of a thin doped a-SiC layer deposited on the top of the cell and the substrate of crystalline silicon are one of the promising alternatives to conventional bulk photovoltaic cells. Lower deposition temperature (≈ 500 K) and higher open circuit voltage are main advantages of above mentioned structures [13, 14]. Passivation layer is an essential part of PV cells. Passivation of the rear side of the solar cell by thin a-SiC layer, which simultaneously serves as a minority carriers reflector, is a suitable replacement for the previously used thin layers based mainly on SiN or SiO_x [15, 16, 17]. Efficiency 9.7 % of unpassivated PV cell was increased by 4 % using a passivation layer $Si_{0,8}C_{0,2}$ [18]. Open circuit voltage approximately 0.7 V can be achieved by optimizing the annealing process and doping the emitter. Intrinsic and doped (n, p) thin films of a-SiC also finds application in the construction of PV cells based on hydrogenated amorphous silicon (a-Si:H). The advantage of a-SiC, as well as a-Si:H, is the possibility of doping with boron or phosphorus to the both conductivity types [19].

III. Experimental Details

Heterojunction solar cell structures which consist of thin p-doped a-SiC film, prepared by PECVD method, deposited on crystalline n-type silicon were studied. The solar cell structures were without transparent conductive oxide, antireflexion and passive layers, as well as other standard solar cell adjustments. The gas mixture in the PECVD reactor was selected as follows: SiH_4 5 sccm, CH_4 3 sccm, B_2H_6 6 sccm. Gas flow of Ar was 10 sccm and of H_2 was 100 sccm, substrate temperature 230 °C, radio frequency power 50 W and pressure 100 Pa was same for all prepared samples. B_2H_6 was a gas mixture 5 % B_2H_6 in H_2. Contacts consists of top grid finger ohmic electrode (~200 nm thick) prepared by lit-off technique and bottom Al ohmic contact (200 nm thick). The prepared solar cell SiC/c-Si heterojunction structure was exposed to elevated temperature 180 °C for 30 min in vacuum furnace.

IV. IMPEDANCE SPECTROSCOPY OF a-SiC/c-Si HETEROJUNCTIONS BEFORE AND AFTER ELEVATED TEMPERATURE TREATMENT

Impedance spectroscopy using sinusoidal voltage (AC) with the amplitude 25 mV and at DC biases from the range –1 to 1 V was used to assess the influence of thermal treatment on the heterostructure properties.

Measured impedance response of SiC/c-Si heterojunction (illustrated by a series of impedance diagrams in Fig. 1.) cannot be fitted by a simple connection of parallel *RC* elements, in complex plain depicted as single arc. The different approach should be applied.

The effect related to inductive process and substantial deformation of the impedance spectra appears at highest forward voltages (Fig. 1f). Radius of the arc decrease with the increase of bias voltage. The presence of the second arc related to different carrier transport process in the impedance spectrum is mainly visible at low forward and at reverse biases.

The AC equivalent circuit of the structure was proposed in order to understand the transport mechanisms and processes. It was found to be useful to combine passive components *R* together with constant phase elements, CPE, to characterize the deviation from Debey-like behavior [20]. CPE is used mainly in the case when frequency dependence of impedance has got a power type (eq. 1, 2).

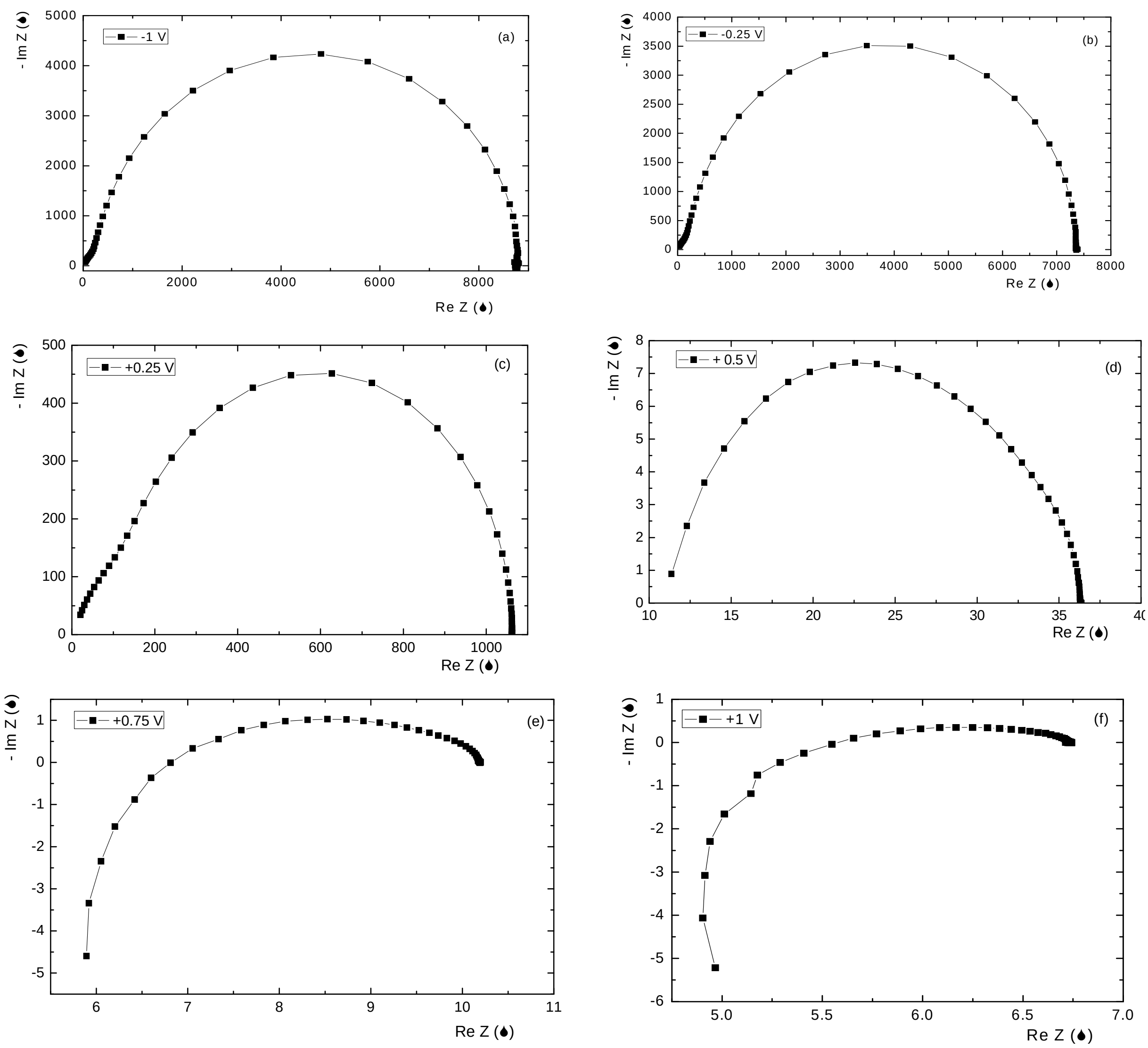

Fig. 1. Cole-Cole plot of a-SiC solar cell structure at different a, b reverse and c, d, e, f forward biases conditions (take into account that the modulus on x and y axes is not the same) measured before exposed to elevated temperature.

$$Y = G_R + G_{CPE} = \frac{1}{R} + \frac{1}{A(j\omega)^n} = \frac{1}{Z} \quad (1)$$

$$Z = \frac{AR(j\omega)^n}{R + A(j\omega)^n} \quad (2)$$

Parameter A is a constant related to CPE capacitance, which is independent on frequency, and n is an exponent that is measure of distortion of semicircular $Z'' = f(Z')$ characteristics. Parameter n is known as "non-ideality" Debey-like curve parameter [21].

AC equivalent circuit (EC) describing the impedance data in Fig.2 was obtained using numerical simulation in Eisanalyser simulation program. Obtained EC consists of series resistance $R1$ and two parallel R-CPE combinations in series. Physical interpretation and equivalent circuit is shown in Fig. 2. Detailed explanation of the equivalent circuit elements of the SiC/c-Si heterostructures can be found in [22].

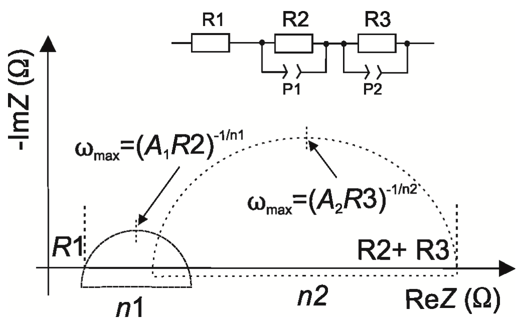

Fig. 2. Cole-Cole plot and representation of equivalent circuit elements.

Series resistance ($R1$) is the total ohmic resistance of heterojunction solar cell structure. This is actually the sum of the parts such as contact resistances, wires and volume resistivity of semiconducting layers. It is little influenced by changes of temperature, illumination and voltage bias, but the treatment at elevated temperature resulted also in the decrease of series resistance.

The series resistance values (point of intersection with the x-axis in Fig. 3.) decreased from 11.5 to 6.5 Ω. The investigated impedance has inductive behavior at high frequencies and higher forward biases (positive ImZ).

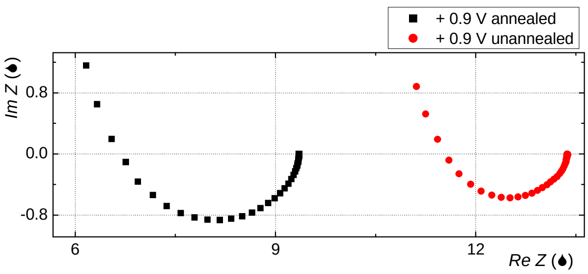

Fig. 3. Cole-Cole plot of a-SiC solar cell structure at – 1 V DC.

Constant phase element (CPE) was introduced into the AC equivalent circuit to represent different inhomogenities such as blocking effects (interfacial states, porosities, etc). The electrical impedance of CPE is expressed as

$$Z_{CPE} = 1/CPE(i\omega)^n \quad (3)$$

The values of exponent of *CPE* dependence for different applied bias are shown in Fig.4. It can be assumed that one R-CPE parallel combination is related to the junction (space charge region) while the second R-CPE combination is related to the different interfaces traps [23].

Nearly constant dependence of $n2$ exponent of CPE element on applied DC bias was found in the dark under reverse bias. The values of exponent $n2$ close to 1 related to CPE impedance element indicate the conventional capacitor behaviour. Exposures to elevated temperatures resulted, on the other hand, also in negative effect. The parameter $n1$ decreased after annealing, what can be simply interpreted as more markedly deviation from Debey-like behavior.

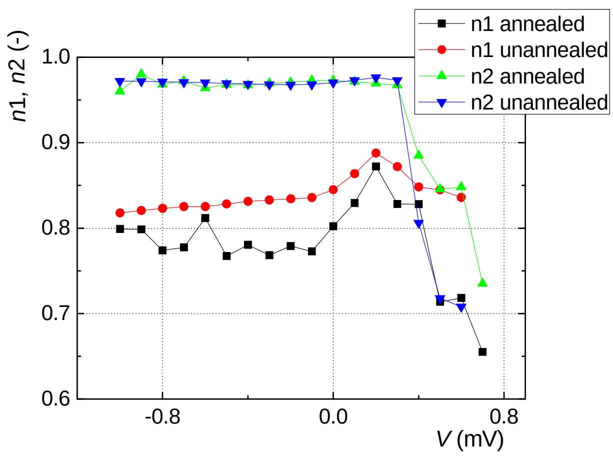

Fig. 4. CPE impedance exponents n1, n2 as a function of applied bias.

Dependence of CPE capacitances at applied bias is shown in Fig.5. The values of capacitances $P1$ and $P2$ are practically independent on the reverse biased voltages. The strong increase of values $P1$ and $P2$ starts at V=0 V going toward forward biases.

Capacitance effects are associated with two types (majority and minority) of charge carriers. Presented capacitance is composed of two components namely transition capacitance and diffusion (dynamic) capacitance.

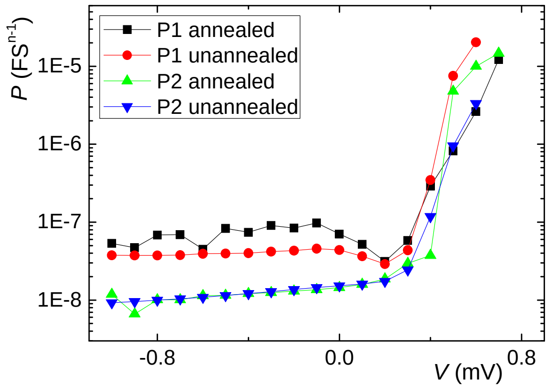

Fig. 5. Constant phase capacitance *P* as a function of the applied bias in the dark.

In negative and low forward biases region, transition or space charge region capacitance is dominant. Diffusion/dynamic capacitance increases in higher forward bias region also under illumination. This process is associated with the injection of minority carriers [23, 24, 25].

Fig.6. shows dependence of obtained parallel resistances on the DC bias voltage. The voltage dependence of resistance indicates two areas dependent on voltage related to shunt (in reverse bias) and dynamic (in forward bias) resistance. Shunt resistance dominates in negative and low forward region. Exposures to elevated temperatures resulted in positive effect – the reduction of parallel conductivity, as shown in Fig. 6.

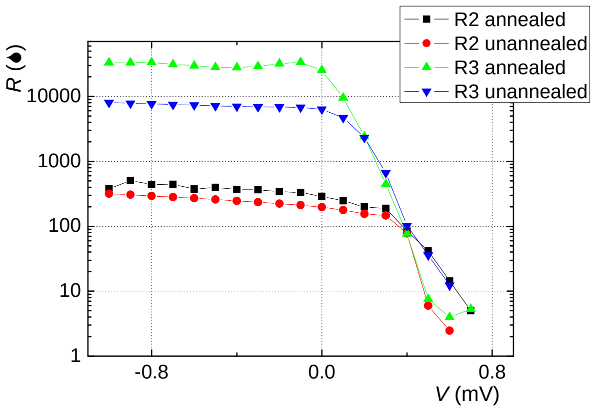

Fig. 6. AC equivalent circuit resistances as a function of applied DC bias.

V. Conclusion

Doped amorphous SiC layers have a great potential in heterojunction solar cell technology. The investigation of AC measurements on chosen sample was in order to demonstrate typical behavior and processes in a-SiC/c-Si structure. Equivalent AC circuit describing the structures was proposed and its elements were discussed. The impedance measurements and subsequent analysis has shown a clear influence of the short treatment at increased temperature on electrical parameters of investigated heterostructural solar cell sample. The series resistance and shunt conductance were positively reduced.

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