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DC AND AC ELECTRIC CHARACTERIZATION OF THIN a–SiC LAYERS FOR PHOTOVOLTAIC APPLICATIONS

Vladimír Šály — Milan Perný — Vladimír Ďurman — Miroslav Mikolášek — Michal Váry — Anton Cerman *

Amorphous silicon carbide (a-SiC) is an excellent passivation layer material for silicon solar cells and a substitution of amorphous silicon in various applications. Thin layers of a-SiC have also been used as optical windows in the construction of tandem solar cells, and located on top of the crystalline silicon substrate they are promising alternatives to conventional homojunction PV cells. This paper summarizes the research activities carried out on thin a-SiC films and reviews the obtained results focused mainly on electrical characterization.

K e y w o r d s: Silicon Carbide, photovoltaics, heterojunction, solar cell

1 INTRODUCTION

Silicon and carbon are basic elements in the evolution of life on this planet. Carbon can be considered as an essential element of living matter. Silicon is an important constituent responsible for technical progress in the 20th century due to its dominant role in microelectronics and later also in photovoltaics. Amorphous structures of a-SiC:H can be prepared by various technological processes. Most often, it is the glow discharge technique GDT [1], PECVD method [2, 3], reactive sputtering [4], RF sputtering [5] and more recently electron-cyclotron resonance (ECR) assisted chemical vapour deposition CVD [6]. Electrical and structural properties of the resulting thin layers depend on the method of deposition, CVD deposition parameters (radio frequency power in the reactor, the reactor chamber pressure and substrate temperature) and the used gaseous hydrocarbon precursors (CH_4, SiH_4, C_2H_2 *etc.*) [7].

Structure a-SiC finds application in optoelectronics mainly due to "tuneability" of its optical and electrical properties. The width of the band gap depends mainly on the ratio of silicon to carbon (Si/C) content in the amorphous alloy. The advantage is also the possibility of doping with phosphorus and nitrogen (n-type semiconductor) and boron (p-type semiconductor). A lightly doped amorphous silicon carbide layer of a-SiC (alternatively modified with other chemical elements, *eg*, nitrogen) forming a heterojunction with crystalline silicon is a relevant substitute for amorphous silicon (a-Si:H). The conversion efficiency up to 22% of heterojunction solar cell (a-Si:H/c-Si) was reported and no further substantial increase is expected [8,9]. In the case of amorphous silicon the problem lies in increased recombination when a thicker layer of a-Si:H is used. The short circuit current I_{sc} of a-Si:H/c-Si solar cell structures is expected to increase when a-Si:H is substituted by a larger band gap material.

Thin layers of a-SiC thus has application as optical windows in the structure of tandem solar cells based on amorphous silicon, photoluminescent LEDs [10] and photodetectors [11]. Amorphous SiC is a promising material used for the third generation PV [12] (*eg*, the concept of matrix quantum wells). The aim is to increase the spectral sensitivity of PV cells.

2 THIN a–SICFILM FOR PV APPLICATION

Heterojunctions consisting of a thin doped a-SiC layer located on the top and the crystalline silicon substrate are promising alternatives to conventional homojunction PV cell with emitter layer and the minority charge carriers reflector on the back side. Lower deposition temperatures around 500 K and higher open circuit voltages are major advantages compared to PV cells based on the homojunction [13]. The top a-SiC film used in heterojunction solar cell has a larger band gap width (1.8 to 2.3 eV) compared with, for example, amorphous silicon (1.7 eV). It is reflected in the reduction of parasitic optical absorption, in an increased short circuit current and a higher open circuit voltage when a thicker amorphous SiC layer is used [14]. Solar cells which consist of a p-type thin layer a-SiC and n-type doped crystalline silicon reach the efficiency 13 % and a fill factor FF = 0.73 [15].

The reason for thin film PV technology research (c-SiTF) is material cost saving looking for substitutes for bulk materials while the efficiency should not be significantly reduced. An example can be the technology known as Recrystallized Wafer Equivalents RexWEs [16] which is based on recrystallization of the deposited thin Si layer by zone heating. Deposited Si is transformed into SiC ceramic and replaces the thick silicon wafer. Another approach is when a sintered SiC layer in the form of ceramic known as RBSiC is used as a substrate. According to [17], an amorphous silicon carbide intermediate layer is a reasonable compromise between the technical and economic

* Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Ilkovičova 3, 81219 Bratislava, Slovakia, milan.perny@stuba.sk

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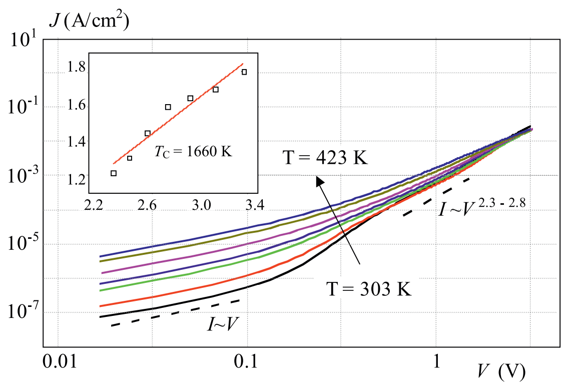

Fig. 1. Current density as a function of applied voltage measured in temperature range 303 to 423 K shown in log-log scheme for sample prepared in cathodic RF mode

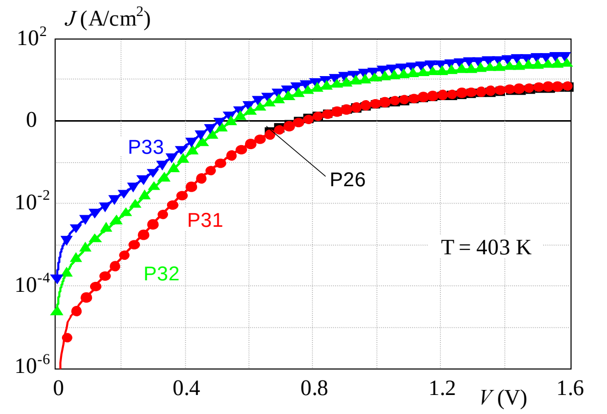

Fig. 2. Current density as a function of applied voltage in forward direction of prepared Al/a-SiC:H/c-Si (p)/Al heterostructures (P31 low and P33 high doping), [24]

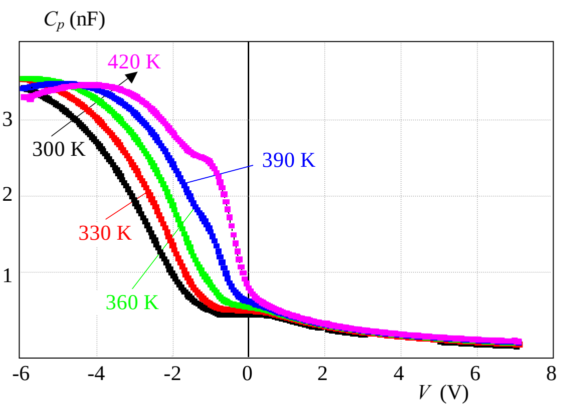

Fig. 3. Capacitance-voltage characteristics of prepared sample at different temperatures (measurement frequency 100 kHz), [26]

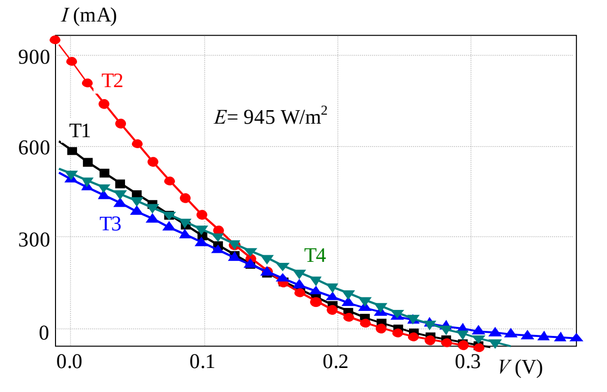

Fig. 4. Illuminated I–V characteristics at room temperature and radiation intensity 945 W.m2, [28]

parameters of c-SiTF cells. a-SiC as an intermediate layer has good adhesion to such a substrate and interaction with the liquid phase forming the active Si layer.

Passivation layers formed from a-SiC are also used in the PV field, at the same time they play the role of the diffusion barrier or reflector of minority charge carriers. Problems of surface passivation of crystalline Si have been studied, *eg*, in [18]. The efficiency of passivated solar cells using the back passivation layer a-$Si_{0.8}C_{0.2}$ was increased by 4% compared with a non-passivated cell with efficiency about 9.7%. Open circuit voltage of about 0.7 V can be achieved by optimizing the process of annealing and doping of the emitter [18]. Glunz *et al*, [19] compared the passivating effect of phosphorus doped and un-doped a-SiC layers. Higher solar cell efficiency (20.3%) was achieved using an undoped layer a-SiC. A fill factor about 81% and open circuit voltage about 0.6 V were obtained in both cases.

Intrinsic or doped (n, p) a-SiC thin films are applicable in hydrogenated amorphous silicon solar cell technology. The advantage of a-Si:H and a-SiC is the possibility of doping with boron or phosphorus to get both types of conductivity. Doped a-SiC together with an intrinsic a-Si:H result in the creation of a potential barrier which serves to separate the light generated charge carriers. Resulting PV cells used glass as a substrate and a transparent conductive oxide as collecting electrode. Increased absorption and open circuit voltage can be achieved in tandem arrangement of individual layers [20-22].

3 THE RESEARCH RESULTS

The studied thin amorphous SiC films were part of heterostructures with p-type crystalline silicon used as a substrate. Attention was particularly focused on their potential use in photovoltaics. The impact of technology on the targeted optical, electrical and structural parameters was taken into account. The influence of the RF PECVD reactor electrode mode on the resulting electrical, structural and topological properties as well as the properties of the heterejonction interface were been studied. Linear approximation of parameter $s - 1$ (Fig. 1). allows determining the characteristic temperature using the Rose model. The inset of the figures describes the determination of characteristic temperature for space charge limitation current mechanism, [23]. Different values of determined characteristic temperatures [23] reflect the impact of the electrode mode. The Rose model employed the analyses of temperature dependences of I–V curves (current density as a function of applied voltage in our case). Characteristic temperature is related to the distribution of defective states in the band gap. The temperature dependence of I–V curves was used also to characterize the electrical transport processes in the structure. Two distinct linear regions can be observed in Fig. 1. The current transport $I = f(V)$ follows the power law. In the high voltage region the current is proportional to a power of bias voltage, $I \approx V^s$, where s is inversely proportional to temperature and ranges from 2.3 to 2.8. More detailed results of this research, when the impact of electrode arrangements was studied, were published for example in [23].

Doping to get p- or n-type of conduction and the possibility to change the conductivity in a wide range is another advantage of a-SiC structures.

The aim of further research was to assess the impact of doping on the resulting electrical and structural parameters. The doping level was controlled via the flow of NH_3 precursor gas in this case. Analysis of the influence of doping showed that higher levels of doping changed the electrical transport mechanism from recombination in the space charge region to multi tunnelling capture-emission mechanism (MTCE) [24], see Fig. 2. While the MTCE process is partially also a trap-assisted tunnelling process, we can assume a higher value of defect concentration in the amorphous silicon carbide layer upon increased concentration of nitrogen. More detail studies were presented in [24, 25].

In some circumstances there is a need to prepare a-SiC at a higher substrate temperature. Preparation of thin layers of a-SiC at high temperature by PECVD was performed and investigation of the impact of high temperature on the resulting electrical and structural parameters was conducted. The I–V characteristics of diode-like structures were measured at various temperatures and analysed to obtain the activation energies, saturation currents and characterization of dominant electrical transport process. Following the measured I–V curves, multitunnelling capture-emission process was identified as the physical phenomenon responsible for the charge transport reflecting the high density of defect states in the forbidden band of amorphous silicon carbide [26].

Amorphous SiC thin films may be used also as thin dielectric layers. Dielectric characterization of samples with incorporated a-SiC were presented in [27]. An example of the results is shown in Fig. 3. Generally, the C–V curve can be described in terms of the accumulation and depletion regions for heterojunction structures. In our case of a-SiC/c-Si(p), deviation from standard C–V curves can be clearly recognized for the investigated samples. One can see the existence of the deep depletion region. It can be assigned to relatively leaky film which prevents formation of an inversion layer. The inversion was not observed even at low frequencies below 1 kHz.

Optimization of a-SiC thin films for HJ solar cells was processed and the results were presented in [28]. The samples were prepared at different substrate temperatures to optimize the technology and improve the quality of the interface. The PECVD technology was used while the substrate temperature was kept as follows $T_1(200\,°\mathrm{C}), T_2(250\,°\mathrm{C}), T_3(300\,°\mathrm{C})$ and $T_4(350\,°\mathrm{C})$. The prepared samples show photovoltaic behaviour and basic PV parameters were determined from current-voltage (I–V) characteristics under light (Fig. 4). Impedance spectroscopy (measurements under dark and illumination) was applied to study the electric properties and an equivalent AC circuit was proposed and discussed [29].

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Vladimír Šály was born in Slovakia in 1956. He graduated from the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava in electrotechnology and in 1985 he received the scientific degree PhD from the same university. Since 2003 he has worked as Associate Professor at SUT FEI. He works in materials science, especially in dielectric and semiconductor structures and photovoltaic renewable energy sources.

Milan Perný was born in Slovakia in 1985. He graduated from the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava in 2009 in materials science. He works in materials science, photovoltaics and renewable energy sources. At present he works at the Institute of Power and Applied Electrical Engineering, Slovak Technical University in Bratislava. His research includes DC and AC diagnostic methods in the field of homojunction and heterojunction solar cells.

Vladimír Ďurman born in Nové Mesto nad Váhom, Slovakia, in 1946, graduated from the Faculty of Electrical Engineering, Slovak University of Technology in electrotechnology in 1968, and received the CSc (PhD) degree in electrotechnology from the same university in 1979. At present he is a research worker at the Institute of Power and Applied Electrical Engineering. He is engaged in the research of dielectrics and dielectric properties of materials.

Miroslav Mikolášek was born in Myjava, Slovakia, in 1983. He received master degree in 2007 and the PhD degree in electronics from the Slovak University of Technology in 2011. At present he works at the Institute of Electronics and Photonics, Slovak Technical University in Bratislava. His interests include simulation and diagnostics of solar cells and the electro-physical properties of heterojunction structures.

Michal Váry was born in Nitra, Slovakia, in 1979. He graduated from the Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technologies, in 2004 and received the PhD degree in electrical engineering materials and technologies in 2009. His research interests include cable insulation systems aging, polarization processes, monitoring of photovoltaic systems performance and aging of photovoltaic systems encapsulation materials.

Anton Cerman was born in Spišská Nová Ves, Slovakia, in 1988. He studied power engineering at the Faculty of Electrical Engineering and Information Technologies of the Slovak University of Technology in Bratislava, where he received his master degree in 2012. Now he is a doctoral student of power engineering focusing his research to effects of grounding on stray currents and stray current mitigation. He is a deputy secretary of the Slovak Member Committee - World Energy Council.