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# Electrical properties of (a-C:H)/Si and (a-C:H)/Ti heterostructures

S. TINCHEV, Y. DYULGERSKA, P. NIKOLOVA*, S. ALEXANDROVA[a], E. VALCHEVA[b]
*Institute of Electronics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee Blvd., 1784 Sofia, Bulgaria*
[a] *Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee Blvd., 1784 Sofia, Bulgaria.*
[b] *Physics Department, Sofia University, 5 J. Baucher, 1164 Sofia, Bulgaria*

Hydrogenated amorphous carbon (a-C:H) is a semiconductor with a band gap which can be easily varied between approximately 1 eV and 2.2 eV. Therefore this material is interesting for electronic applications. We report here the results of our investigation of the electrical properties of (a-C:H)/Si and (a-C:H)/Ti heterostructures. Thin films of hydrogenated amorphous carbon were made by plasma enhanced chemical vapor deposition (PECVD) from benzene. Electrical contacts were deposited by DC magnetron sputtering. The current-voltage (I-V), capacitance-voltage (C-V) and conductance-voltage (G-V) characteristics of the heterostructures were measured. The (a-C:H)/Ti heterostructure did not manifest Schottky contact behavior. The (a-C:H)/Si structure with a Ti electrode behaved like a p-n junction, but at higher voltages the current increase was limited by the bulk resistance of the a-C:H film.

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*Keywords*: Hydrogenated amorphous carbon, Electrical properties, Heterostructures

## 1. Introduction

Hydrogenated amorphous carbon (a-C:H) thin films have many interesting properties. Nowadays the most important applications make use mainly of their excellent mechanical properties – high hardness and low friction. The a-C:H films are also suitable for optical applications because of their good transparency in the visible and in the infrared wavelength ranges [1]. For electronics [2,3], it is very important that this material is a semiconductor with a band gap which can be easily varied between approximately 1 and 2.2 eV. However, the a-C:H electronic properties include a large density of mid-gap states, wide band tails, low carrier mobility and poor doping response [4]. This is the reason why the only large scale application of amorphous carbon in electronics is as a protection coating of computer hard disks where only the mechanical properties of the material are employed [5]. Nevertheless, there is still hope that a-C:H thin films can find other applications in electronics, for example, for electron field emitters [6] or high reverse breakdown a-C:H/Si diodes [7]. Therefore, it is important to study the electrical properties of heterostructures of this material with the most popular semiconducting material (Si) and different metals.

In this paper, we report the results of our investigations on the electrical properties of heterostructures of hydrogenated amorphous carbon (a-C:H) with Si and Ti.

## 2. Experimental

### 2.1. Sample preparation

The structures studied in the present work are shown in Fig. 1. The deposition of a-C:H films was carried out in a parallel-plate DC PECVD reactor. The films were deposited at a DC voltage of 1 kV and at $5.10^{-2}$ Torr from a mixture of benzene and argon. The deposition was carried out for 30 min. and the thickness of the films was about 160 nm. The films were deposited on 4-7 Ω.cm <100> p-Si or on Ti films. The titanium (Ti) films were deposited on <100> p-Si by magnetron sputtering. In both cases, 10 min Ar ion sputtering at 1 kV was carried out before deposition. Top Ti-electrodes were deposited through a shadow mask with a circular aperture of diameter 1mm.

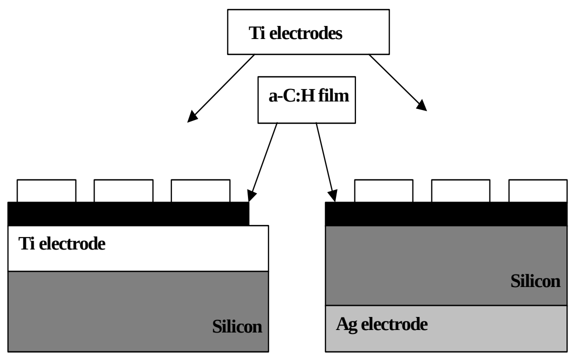


*Fig. 1. (a-C:H )/ Ti and (a-C:H )/ Si heterostructures.*

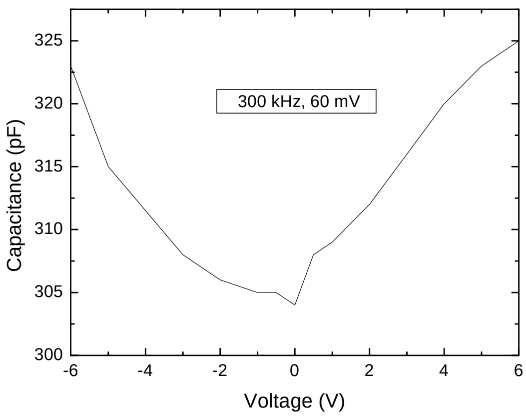


*Fig. 2. Current-voltage characteristic of a Ti /(a-C:H)/ Ti heterostructure.*

The structures were not subjected either to an intentional temperature increase during deposition nor to annealing.

### 2.2. Experimental measurements

The measurements of the I-V, C-V and G-V characteristics were carried out at room temperature in the dark. A Hewlett-Packard Model 4140 pA-meter/dc voltage source and a precision component analyzer Wayneker 6425 were used. The C-V and G-V characteristics were measured in the 50 - 300 kHz frequency range.

## 3. Results

Fig. 2 shows the current-voltage characteristic of a Ti/(a-C:H)/Ti heterostructure. The I-V characteristic is symmetrical for the applied voltages. However, the two branches of the I-V characteristics are not fully identical. This is an indication that the two interfaces of (a-C:H)/Ti are not identical.

Fig. 3 shows the capacitance of the Ti/a-C:H/Ti heterostructure as a function of the applied voltage. The capacitance is not a constant and increases with the applied voltage in both directions. From the C-V characteristic, it is again evident that the Ti/(a-C:H) and (a-C:H)/Ti interfaces are not identical. Regarding the Ti/(a-C:H)/Ti heterostructure as parallel plate capacitor, one can calculate the dielectric constant of the a-C:H material as 7.02 at V=0. Typical values of the a-C:H thin films dielectric constant are ($4<\varepsilon<9$) [8].

We have found that the AC conductance increased with applied voltage - Fig. 4. For zero DC applied voltage and 60 mV AC amplitude at 300 kHz we measured a value of 60 μS. For our geometry, this yields a rough estimation of the electrical resistivity (ρ) of the a-C:H material of about $8.2 \cdot 10^4$ Ω.m. Typical values of the a-C:H thin film resistivity are ($\rho > 10^4$ Ω.m) [8].

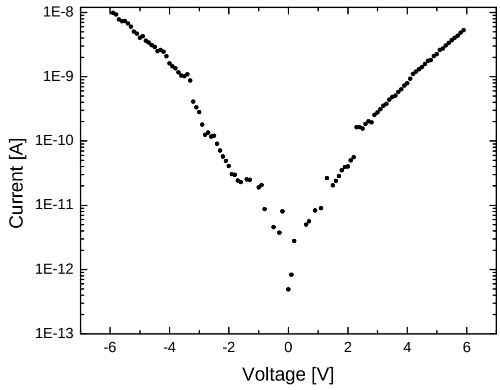


*Fig. 3. Capacitance-voltage characteristic of a Ti /(a-C:H) / Ti heterostructure.*

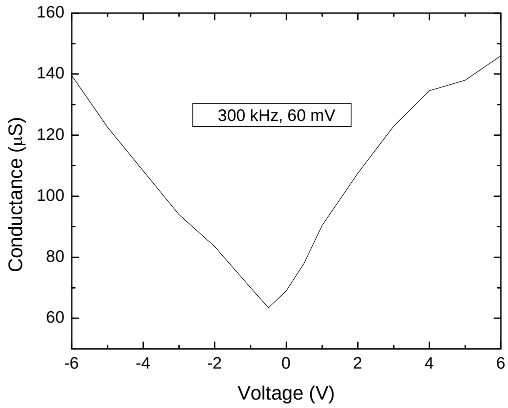


*Fig. 4. Conductance-voltage characteristic of a Ti/(a-C:H) / Ti heterostructure.*

Fig. 5 shows the I-V characteristics of a Ti/(a-C:H)/Si heterostructure. The well-known p-n junction equation (1) can be used for an approximate description of the I-V dependency of the investigated heterostructure:

$$I = I_S\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right] \qquad (1)$$

where $e$ is the electron charge, $V$ is the applied voltage, $\eta$ is the ideality factor, $k$ is Boltzmann constant and $T$ is the temperature. $I_S$ is the saturation current. At high injection levels, the simplified form of the equation, together with the results presented in Fig.5, were used to experimentally determine the values of $I_S$ and $\eta$ of the Ti/(a-C:H)/p-Si structure with a Ag back contact at $T$=300 K: $I_S = 8.8\ 10^{-10}$ A and $\eta = 8.58$.

In the case of conventional p-n junctions, the value of the ideality factor is known to vary between 1 and 2, but values as high as $\eta$ = 6.29 at T=300 K are reported for the case of Au/DLC/ p-Si/Ag heterostructures [8]. The other authors suggested that such a high value of $\eta$ is associated with a hopping mechanism of charge transport in amorphous films [9]. The forward bias characteristics exhibited a turn-on voltage of about 1V. In the reverse bias region, an almost linear current dependence on the applied voltage was observed (inset).

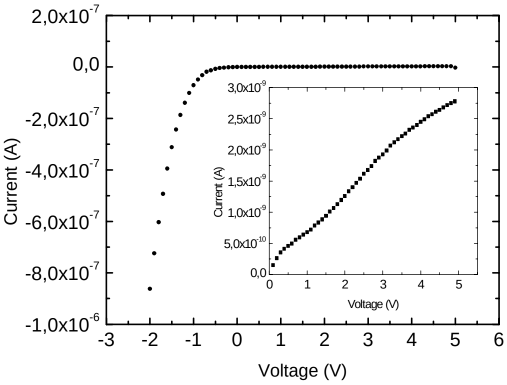


*Fig. 5. Current-voltage characteristic of a Ti /(a-C:H) /Si heterostructure.*

However, the current is about two orders of amplitude smaller. Thus, the rectification ratio of our (a-C:H)/Si heterostructures exceeds $10^2$, which is an encouraging result for the possible electronic applications of amorphous carbon.

The typical result of C-V measurements of the Ti/(a-C:H)/Si system in both directions is shown in Fig.6. Three regions with different slopes can be clearly distinguished: a nearly flat region for - 2V < U < 2V and two more steep regions for voltages / U / > 2V.

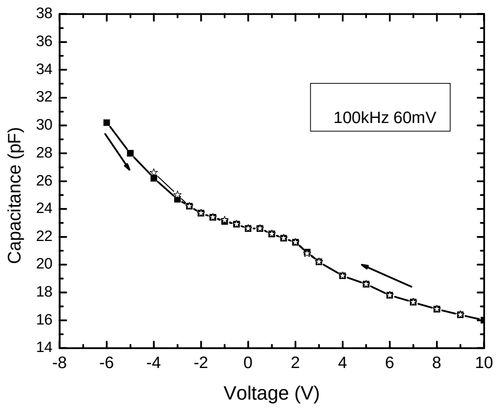


*Fig. 6. Capacitance-voltage characteristic of a Ti /(a-C:H) /Si heterostructure.*

## 4. Discussion

The possible applications of a-C:H thin films for electronic devices are based on the well-known electrical properties of various heterojunctions which include such films. There is no theory, however, which can give a satisfactory description of the electrical properties of heterostructures with amorphous thin films of low conductivity, where the predominant mechanism of charge transport is hopping of charge carriers among localized states, as was found to be the case in amorphous carbon thin films [10].

The electrical characterization of the Ti/(a-C:H)/Ti structure is indicative of a bulk-limited Schottky conduction mechanism in the a-C:H film according to [6] and can be attributed to $sp^2$ rich regions [11,12]. The structure did not exhibit Schottky barrier formation. The $sp^2$ assumption is based on the method of fabrication (the enhanced temperature during magnetron deposition of the circular Ti dots on top of the a-C:H layer leads to graphitization of its surface [13]. The C-V characteristic (Fig. 3) which manifests an increase in the capacitance with the voltage applied is another indication of the absence of a Schottky junction whose depletion layer (if present) would cause just the opposite dependence (a decrease of the capacitance with the applied voltage).

The analysis of the I-V characteristics of a Ti/(a-C:H)/Si heterostructure from Fig.5 shows that the rectifying behavior strongly depends on the applied voltage. At lower voltages, the conduction is usually limited by the (a-C:H)/Si. At higher voltages, the conduction becomes limited by the bulk resistance of the a-C:H film. The change of the slope of the C-V characteristic (Fig. 6) can be explained by a non-uniform distribution of the effective concentration of the charge carriers in the bulk of the a-C:H film.

## 5. Conclusions

The electrical properties a-C:H thin films deposited from benzene by DC PECVD were investigated. The analysis of the I-V, C-V and G-V curves of the samples characterized a-C:H as a high resistivity semiconductor. The (a-C:H)/Ti heterostructure did not manifest Schottky diode behavior. The (a-C:H)/Si structure with a Ti electrode behaved like a p-n junction, but at higher voltages the current increase was limited by the bulk resistance of the a-C:H film.

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*Corresponding author: petranka@ie.bas.bg