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LETTER

Electrical properties of flash-evaporated carbon nanolayers on PTFE

T. Hubáček · O. Lyutakov · V. Rybka · V. Švorčík

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Potential application of flash-deposited carbon layers depends crucially on their mechanical properties [1, 2]. For applications in electron microscopy the layer thickness, homogeneity and electrical conductivity are of utmost importance [3]. Interaction with living cells was recently found to depend on chemical composition, polarity and electrical conductance of carbon layer [4, 5].

In our previous work [1] it was shown that the thickness of the flash-evaporated carbon layer decreases monotonously with increasing distance between the carbon filament and the substrate. The carbon layers, prepared by the flash deposition, were shown to contain significant fractions of oxygen, hydrogen and amorphous carbon (a-C:H). The carbon deposition results in dramatic decrease of the sheet resistance of the carbon–polymer composite.

The present work is a continuation of our previous study of the properties of the flash-evaporated carbon layers. The temperature dependence of the sheet resistance (R_s) of the carbon layers was studied with the aim to determine mechanism of the charge transport. Also the V–A characteristics were measured and the value of the optical gap (E_g^{opt}) determined from UV–Vis spectra.

Polytetrafluoroethylene (PTFE, Goodfellow, UK) in the form of 50 μm sheets, were used in the present experiments as carbon layer backing. Carbon layers were prepared using the SCD 050 Carbon Thread Evaporation Device by flash evaporation from carbon filaments (BAL-TEC). Preliminary degassing of the filament was performed at the pressure of 4 Pa and at room temperature (RT). The distance between the filament and the PTFE substrate was 2 cm. The typical thickness of the carbon layers was about 70 nm [1].

For optical measurements the carbon layers were deposited onto SiO_2 substrate. UV–Vis spectra in the spectral range 200–3000 nm were obtained using Shimadzu UV-3600 Spectrometer [6]. Spectra were evaluated in a standard way and the optical gap width (E_g^{opt}) of the carbon layers was estimated, according to Tauc's relation [6, 7] from extrapolated linear part of the $(\alpha hv)^x$ vs. hv dependence ($x = ½$, indirect electron transition). Sheet resistance (R_s) was measured by means of a Keithley device using a standard two-point technique at RT. For the determination of the temperature dependence of the resistance, the samples were placed in a liquid nitrogen (LN_2) cryostat, evacuated to the pressure of about 10^{-4} Pa. The samples were first cooled and then gradually heated up to the temperature of 373 K at a speed of 15 K/h. Current–Voltage (CV) characteristics of carbon layers was determined at liquid nitrogen temperature using a standard technique.

According to our previous results [1] the present conditions of the layer deposition were chosen to obtain about 70 nm thick carbon layers. For the measurement of the sheet resistance R_s as a function of the temperature, the C/PTFE samples were placed in the cryostat cooled by LN_2. Temperature dependence of the sheet resistance, measured in the temperature range from 80 to 350 K, is shown in Fig. 1. One can see that over a broad temperature range the sheet resistance decreases rapidly with increasing temperature. The decrease is typical for semiconductors; semiconductance of amorphous carbon (a-C) was reported earlier, e.g. in Ref. [8].

It is believed that the mechanism of the charge transport in carbon layers proceeds according to variable range hopping (VRH) mechanism, suggested by Mott [9, 10],

T. Hubáček · O. Lyutakov · V. Rybka · V. Švorčík (✉)
Department of Solid State Engineering, Institute of Chemical Technology, 166 28 Prague, Czech Republic
e-mail: vaclav.svorcik@vscht.cz

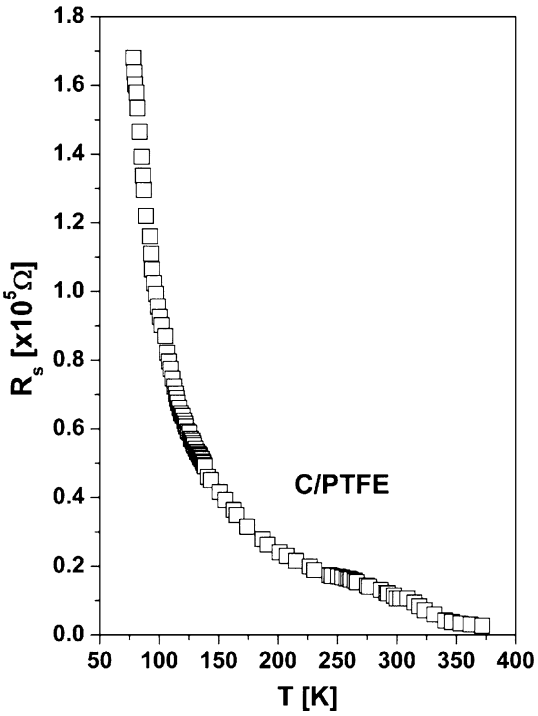

Fig. 1 Temperature dependence of the sheet resistance (R_s) for carbon layer, 70 nm thick, flash evaporated onto PTFE

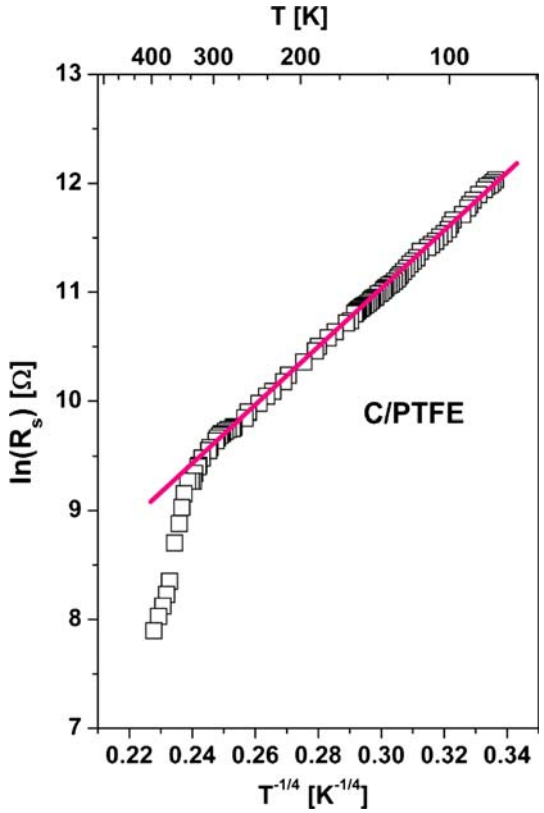

Fig. 2 Temperature dependence of the sheet resistance R_s in form ln R_s vs. $T^{-1/4}$ for the same sample as in Fig. 1

which depends on the density of the states present near the Fermi level [11]. The VRH model leads to the dependence $R_s(T) \approx \exp((T_0/T)^{1/4})$, where T_0 is an adjustable parameter. The same dependence as in Fig. 1 is shown in Fig. 2 in ln $R_s(T)$ vs. $T^{-1/4}$ representation. One can see that the VRH model describes well the charge transport in the temperature range from 80 to 350 K. It is supposed that the electron states are localised on carbon clusters sp^2, dispersed randomly within the carbon layer. After application of an external electrical field electron hopping between the clusters takes place. The electron movement proceeds via phonon-assisted tunneling and with decreasing temperature the electrons tend to hop to larger distances on sites which are energetically closer than the nearest neighbour.

The dependence of the electrical current (I) on the applied voltage (U) (CV dependence) measured at LN_2 temperature is shown in Fig. 3. The carbon layer exhibits non-linear I vs. U dependence indicating pronounced deviation from ohmic behaviour.

The values of the optical gap width (E_g^{opt}) of the carbon layers with different structures have been reported. They lie between a minimum ($E_g^{opt} = 0$ eV) for graphite and a maximum ($E_g^{opt} = 5.48$ eV) for diamond [12]. Experimentally the optical gap width can be determined from observable phenomena related to the electron transitions between valence and conductance bands. The transitions can be initiated thermally (E_g^{term}) or by photon absorption (E_g^{opt}). Here the optical gap width (E_g^{opt}) was determined

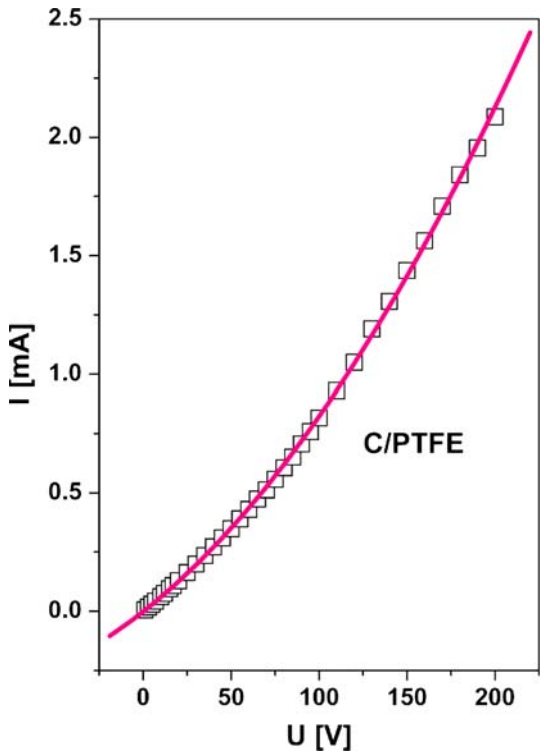

Fig. 3 CV characteristics dependence measured at liquid nitrogen temperature from the same sample as in Fig. 1

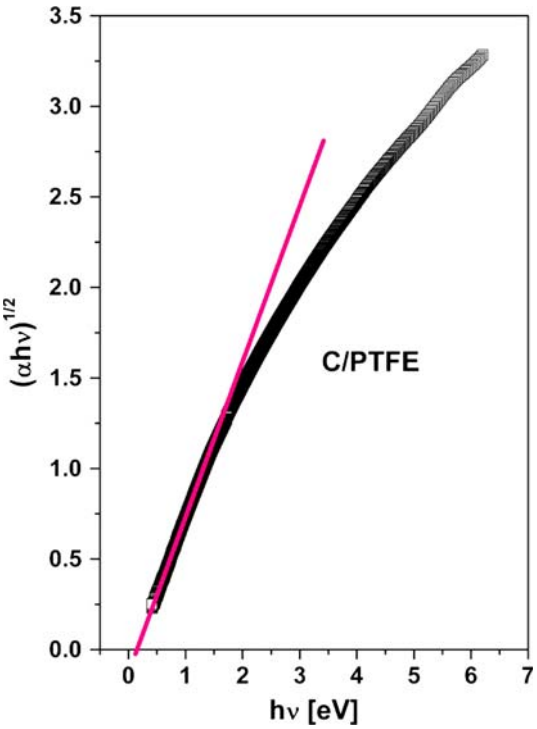

Fig. 4 Tauc's plot $(\alpha h\upsilon)^{1/2}$ vs. $h\upsilon$ deduced from UV–Vis spectra taken from the same sample as in Fig. 1

from measured UV–Vis spectra using well-known Tauc's relation [7]. The dependence $[(\alpha h\upsilon)^{1/2}$ vs. $h\upsilon]$ is shown in Fig. 4. By an extrapolation shown in Fig. 4 the value of the optical gap width $E_g^{opt} = 0.1$ eV was estimated. This value is close to the energy gap of graphite. It is supposed that the estimated E_g^{opt} corresponds to electron transitions between band edges of valence and conductance bands of sp^2 carbon atoms, taking part in VRH conductivity mechanism. Other, larger values of E_g^{opt} may play a role too. It should be noted that electrical width of the band gap may be larger that optical ones due to additional energy needed for dissociation of exciton pair [11].

The electrical resistance of the carbon layers deposited onto PTFE by flash evaporation was measured as a function of the sample temperature. Monotonous decrease of the layer resistance with increasing temperature indicates semiconducting character of the carbon layers. The charge transport in the temperature range from 80 to 350 K is well described by Mott's variable range hopping mechanism. The layers exhibit non-linear dependence of the electrical current on the applied voltage which indicates departure from ohmic mechanism of the charge transport. The optical gap width was determined to be $E_g^{opt} = 0.1$ eV from UV–Vis spectra.

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