# Dependence of the conductivity of PEDOT:PSS films on the deposition method

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Recently, method of obtaining hybrid flexible transparent conducting films for organic light emitting devices, consisting of carbon nanotubes and transparent conducting polymer PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate), was proposed in [1]. Such hybrid films with high conductivity and transparency are essential for wide variety optoelectronic and photovoltaic devices [2].

In this work, we compared two methods of fabricating composite conductive films, consisting of PEDOT:PSS and single walled carbon nanotubes (SWCNT) inclusions in order to obtain polymer films with higher conductivity and transparency for their use in solar cell structures based on Si.

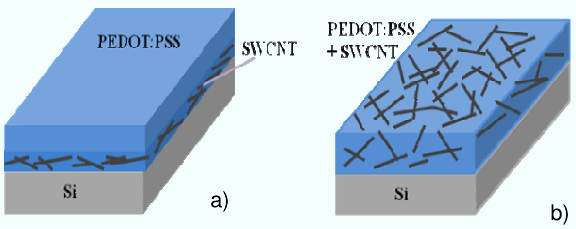
## Experimental details

Factory polished *n*-Si (100) phosphorus-doped wafers (resistivity of 1…10 Ohm·cm) were used as substrate for film depositions.

According to the first method used for film fabrications the SWCNT layers were deposited by repeated immersion (*n*=1, 2, 4 and 8) from a suspension of SWCNT in dimethylformamide (DMF) on the Si substrate. Subsequently a thin (200-300 nm) layer of PEDOT:PSS was deposited by spin-coating technique.

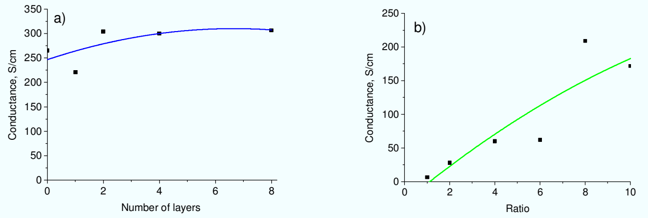
The second method used consisted in obtaining stable PEDOT:PSS-SWCNT suspension (with using of DMF and TRITON X100 with different v/v ratios). One layer of such suspension was deposited by spin-coating on the Si substrate.

All samples were annealed at a temperature of 135-150°C.




Schematic representation of the structures design based on PEDOT:PSS/SWCNT (a) and PEDOT:PSS+SWCNT (b) composite films on the flat surface of Si.

## Electrical characteristics




Dependence of the conductivity of PEDOT:PSS/SWCNT on the number of SWCNT layers (a) and composite films PEDOT:PSS + SWCNT on PEDOT:PSS to (DMF + SWCNT) ratio (b), obtained from 4-point probe technique measurements (with CHI-660 instrument).

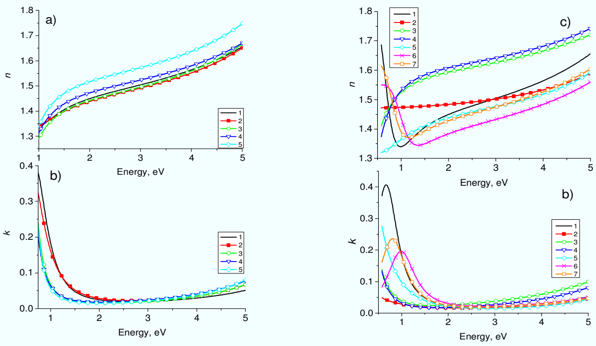
**Table 1.** Thickness and electrical parameters of PEDOT:PSS/SWCNT films.

| Number of SWCNT layers | *d*, nm | $R_{SQ}$, Ohm/SQ | ρ, Ohm·cm | σ, S/cm |
|---|---|---|---|---|
| 0 | 222.0 | 169.7 | 0.004 | 265.5 |
| 1 | 279.3 | 162.1 | 0.0045 | 220.9 |
| 2 | 276.8 | 118.9 | 0.0033 | 303.9 |
| 4 | 375.5 | 88.8 | 0.0033 | 300.0 |
| 8 | 328.0 | 99.5 | 0.0033 | 306.5 |

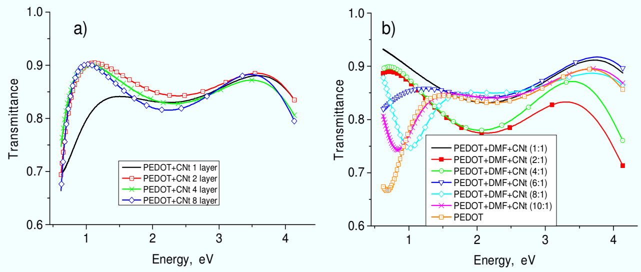
**Table 2.** Thickness and electrical parameters of composite PEDOT:PSS + ((DMF + SWCNT) + 4% TRITON X100) films.

| PEDOT:PSS to (DMF+SWCNT) ratio | *d*, nm | $R_{SQ}$, Ohm/SQ | ρ, Ohm·cm | σ, S/cm |
|---|---|---|---|---|
| (1:1) | 418 | 3696.5 | 0.155 | 6.5 |
| (2:1) | 335 | 1060.3 | 0.036 | 28.2 |
| (4:1) | 313 | 530.7 | 0.017 | 60.2 |
| (6:1) | 312 | 517.0 | 0.016 | 62.1 |
| (8:1) | 220 | 217.5 | 0.005 | 209.0 |
| (10:1) | 225 | 258.6 | 0.006 | 172.0 |
| pure PEDOT:PSS | 222 | 169.7 | 0.004 | 265.5 |

## Optical properties of deposited PEDOT:PSS composite films




The dependences *n*(λ) and *k*(λ) for conductive films PEDOT:PSS/SWCNT with number of SWCNT layers: 0 (*1*), 1 (*2*), 2 (*3*), 4 (*4*), 8 (*5*) (a, b) and PEDOT:PSS + ((DMF + SWCNT) + 4% TRITON X100) with the PEDOT:PSS to (DMF + SWCNT) ratio: pure PEDOT:PSS (*1*), (1:1) (*2*), (2:1) (*3*), (4:1) (*4*), (6:1) (*5*), (8:1) (*6*), (10:1) (*7*) (c, d), determined from spectroscopic ellipsometry measurements (with SE-2000 instrument).




Calculated transmittance of PEDOT:PSS/SWCNT (a) and PEDOT:PSS + SWCNT (b) composite films with 100 nm thickness.

## CONCLUSIONS

* Two methods for fabrication of composite conductive films, consisting of PEDOT:PSS and single-walled carbon nanotubes inclusions were compared to obtain films with higher conductivity and transparency for their use in solar cell structures based on Si. The thickness and optical parameters of the films were determined using spectroscopic ellipsometry within the energy range 0.6…5.0 eV.
* The electrophysical parameters were obtained from the 4-point probe measurements. Our results have shown that the method of sequential deposition of SWCNT then PEDOT:PSS enables to obtain films with a much higher conductivity (220…306 S/cm) as compared to the method based on application of films prepared from the colloidal solution of SWCNT in PEDOT:PSS (6…209 S/cm).
* The transmittance of the films of both types has shown the high value close to 80…90%, but it is a bit enhanced in the NIR range for the films with sequential deposition of SWCNT and PEDOT. This is related with the lower value of extinction coefficient *k*(λ) for these films in this range.

[1] H.-Y. Hao, L. Dai, Z. Li, K.-H. Low. Enhanced Conductivity and Color Neutrality of Transparent Conductive Electrodes Based on CNT/PEDOT:PSS Composite with a Layer-by-Layer Structure // Advanced Material Engineering. – 2015. – p. 285 – 290.
[2] S.V. Mamykin, O.S. Kondratenko, I.B. Mamontova, T.S. Lunko, N.V. Kotova, T.R. Barlas. Solar Cells Based on the PEDOT:PSS/Si Heterojunction with Ag Nanoparticles // Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal, Online. – 2020. – 1BV.4.51. – ISBN 3-936338-73-6.