SWCNT Transparent Conducting Films: Towards the Theoretical Limit

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Electrically conducting thin-film materials possessing high transmittance are critical elements for many optoelectronic devices. Nowadays, the advancement of the transparent conductor applications requires the replacement of indium tin oxide (ITO), which at the moment is the key material in electronics. Single-walled carbon nanotube (SWCNT) films were proposed to be a cheap alternative for the transparent conductive film (TCF) production due to their unique mechanical properties, such as flexibility and stretchability. Here, we analyze the latest advancement in the optoelectronic performance of TCFs based on SWCNTs. We describe the roadmap for further research and development of TCFs be means of "rational design", which breaks the deadlock for the obtaining of TCFs close to the theoretically limited performance.

First, we propose to use machine learning techniques such as artificial neural networks [1] and support vector regression [2] to process the experimental data and to predict the performance of the aerosol CVD synthesis of SWCNTs and to enhance the SWCNT thin-film performance for transparent and conducting applications. The predictive model trained on the experimental data allowed to achieve the synthesis conditions toward the advanced optoelectronic performance of multiparameter processes such as nanotube growth. Using gold chloride as the most effective dopant for the SWCNTs, we improve their optoelectrical characteristics by optimizing the doping conditions [3]. Doping of the improved carbon nanotube films with $HAuCl_4$ results in the equivalent sheet resistance of 39 Ω/□.

For the first time we demonstrate that electrochemical doping of SWCNTs can be successfully applied in transparent electronics. This method provided fine and reversible tuning of the optoelectrical properties of the material over a wide range of sheet resistances and transmittances. A wide electrochemical window imidazolium-based (BMIM-PF_6) ionic liquid allowed us to achieve the Fermi level shift up to 1.4 eV and an equivalent sheet resistance (sheet resistance of the film with the 90% transmittance at 550 nm) value of 53 Ω/sq for the SWCNT films. The results open new avenues for electrochemical control and fine-tuning of the electronic structure of carbon nanomaterials for rigid and flexible highly conductive and transparent device applications. We report that the electrochemical doping can tailor nonlinear optical absorption of SWCNT films and demonstrate its application to control pulsed fiber laser generation [4]. With a pump–probe technique, we show that under an applied voltage below 2 V the photobleaching of the material can be gradually reduced and even turned to photoinduced absorption. We show that the pulse generation regime can be reversibly switched between femtosecond mode-locking and microsecond Q-switching using different gate voltages. This approach paves the road toward carbon nanotube optical devices with tunable nonlinearity.

Here, we develop a novel transparent p-type flexible electrode based on SWCNTs combined with poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), molybdenum oxide and SWCNT fibers [5]. We achieved a record equivalent sheet resistance of 17 Ω/sq with a transmittance of 90% at 550 nm and a high degree of flexibility. We demonstrate that our solar cells based on the proposed electrode and hydrogenated amorphous silicon (a-Si:H) yield an outstanding short-circuit current density of J_{sc} = 15.03 mA/cm^2 and a record power conversion efficiency of PCE = 8.8% for SWCNTs/a-Si:H hybrid solar cells.

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