Aerosol CVD synthesised single-walled carbon nanotube for conductive and transparent film fabrication

Albert G. Nasibulin[1,2], Aleksandra Gorkina[2], Evgenia Gilshteyn[2]

[1] Department of Applied Physics, Aalto University, Espoo, Finland
[2] Skolkovo Institute of Science and Technology, Nobel str. 3, 143026, Moscow, Russia

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Presenting author email: a.nasibulin@skoltech.fi

Among various carbon nanotube (CNT) properties, optical transparency and electrical conductivity are the most important for electronics and photonics applications, such as transistors, printed electronics, touch screens, sensors, photonic devices, electrodes for solar cells lightning and display devices. Thick and highly porous CNT films are interesting for fuel cells, water and air purification applications. As the CNT synthesis and film fabrication processes develop, optoelectronic performance of the CNT network constantly improves however has not achieved yet the conductivity at a given transparency of indium tin oxide (ITO) films on a glass substrate. Main advantages of the CNT thin films over the ITO are their flexibility, low reflectivity and cost of raw material resources. The deposition of CNTs on a flexible substrate like PET allows fabrication of transparent and flexible devices, while ITO is a brittle material and must be deposited on rigid substrate. Furthermore, indium is a rare but crucial element in display screens manufacturing industry; therefore its scarcity and massive industrial need is an issue of the speculative market price.

CNT films with excellent optoelectronic properties close to ITO on flexible substrate have been already fabricated with the aerosol synthesis method based on CO disproportionation. They were used to demonstrate the state-of-the-art performance of the transparent electrodes in electrochemical sensors, ultrafast femtosecond laser absorbers, thermoacoustic loudspeaker, aerosol filters, gas flowmeters and heaters. Those CNT films have outstanding properties, however, CO disproportionation reaction is slow and limited thermodynamically. Unless performed at high pressure, CO based processes have relatively low yield, which makes the fabrication of thick and/or high area CNT layers expensive. This might be an obstacle to transfer this technology to industrial applications, where high throughput is expected. The yield of the CNTs can be increased at high CO pressures, which however would make the processing of the toxic and explosive CO gas quite demanding. Moreover, an ambient pressure film fabrication, which a prerequisite for cheap production of materials to be competitive with existing technology for transparent and flexible electronics, would not be possible.

Therefore, we considered a different carbon source that would allow producing CNTs at ambient pressure with a higher production rate and compatible with a direct dry press transfer technique introduced by our group for CNT thin fabrication (Kaskela *et al.*, 2010). Hydrocarbons are obviously good candidates for higher reaction yield (Reynaud *et al.*, 2014). They have been used extensively as a carbon source for the CNT synthesis since the early years of the captivating journey , although before this contribution, no attempt has been done to fabricate highly conductive layer by direct gas filtration and subsequent dry transferring of CNTs onto final substrate.

In this work, we focused on continuous CNT synthesis process based on hydrocarbon and fast fabrication of CNT thin films by dry transfer technique, in which the reaction products are directly and continuously collected from the gas phase. The product was collected downstream of the reactor by filtering the flow in the form of thin films with adjustable thicknesses (transmittance) and subsequently transferred on a desirable substrate by a dry transfer technique.

To further improve conductivity of the films we prepared a novel hybrid CNT-graphene nanomaterial by graphene oxide aerosol deposition on top of CNT films (Gorkina *et al.*, 2016). The graphene oxide was then reduced by thermal annealing at ambient atmosphere or in H_2 atmosphere. At the final step the CNT-graphene hybrids were chemically doped using gold(III) chloride. As a result, we show that the hybrids demonstrate excellent optoelectrical performance with the sheet resistance as low as 73 Ω/□ at 90% transmittance.

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