Polymer-wrapped carbon nanotubes for high performance field effect transistors

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Summary

The growth of the societal demand for fast and low energy consumption electronics in the last few decades demands improvements of the performance of electronic devices together with the miniaturization of their dimensions. Nevertheless, the active channel material for transistors has remained unchanged by far. And the further advancement of conventional Si-technology is hampered by technological limits such as quantum tunneling, which reduces device thermal efficiency, and the complicated and expensive lithography processes required to further reduce the active channel size. These reasons force to explore alternatives, which could allow maintaining or improving the actual performances, with larger miniaturization, but with lower power consumption. One of the best candidates for these tasks are single-walled carbon nanotubes (SWNTs). Semiconducting single-walled carbon nanotubes (s-SWNTs) used as transistor channel have demonstrated extraordinary high carrier mobility of up to 100 000 $cm^2V^{-1}s^{-1}$ compared to 1400 $cm^2V^{-1}s^{-1}$ for Si. The band gaps of the sSWNTs are inversely proportional to the diameter (around 1nm) and are of a typical value around 1 eV, which makes them perfect for transistor application. The presence of a real band gap allows to turn-off the device and makes high on/off ratio achievable, in comparison with the other nanocarbon candidate, graphene.

In order to be a good alternative for existing technologies, carbon nanotube transistors must meet requirements such as high mobility and on/off ratio, cheap and easy processability, large-scale and reproducible fabrication. Up to date, high-performance in carbon nanotube transistors were achieved by growing nanotubes using chemical vapor deposition with subsequent transfer to the substrate and contact metallization by electron beam lithography. Here we utilize polymer-assisted nanotubes separation for transistor application aiming to fabricate the high-performance device using the prepared nanotubes dispersion and develop scalable and reproducible SWNT deposition technique.

Chapter 2 explains how a simple deposition technique, such as Blade Coating, can significantly improve device performance by SWNT alignment. Another demonstrated advantage of this technique over spin-coating and drop-casting methods are better process scalability and reproducibility. Here we also demonstrated that the wrapping polymer not only influences the SWNT selection process but also the device performance itself. FETs based on PF12-wrapped SWNTs show almost symmetric ambipolar characteristics with an

equal hole and electron current branches, while the transistors fabricated with P3DDT-wrapped SWNTs show significantly reduced electron current.

Chapter 3 reports a detailed study of the charge carrier transport mechanisms in ambipolar FETs of semi-aligned SWNTs. An anomalous temperature-dependent nonlinear transport behavior, observed in large-diameter SWNTs, suggests an interplay between the intrinsic transport of individual tubes and the percolative network properties, highlighting the nature of polymer-wrapped SWNTs as a complex hybrid material.

In order to fabricate high-performing transistors, it is very important to obtain SWNT inks of very high purity and concentration. Using a novel poly(2,5-dimethylidynenitrilo-3,4-didodecylthienylene) (PAMDD) polymer we succeeded to obtain highly concentrated solutions of sSWNTs. Aiming to investigate the metallic content of the inks, we fabricated and analyzed transistors with source-drain separation not exceeding the average SWNT length. **Chapter 4** presents a statistics over 190 fabricated 300 nm channel length devices with the total SWNTs number of 646. Due to the absence of shorts circuits during the electrical characterization, we estimate the purity of the solution to be more than 99.9%.

In **Chapter 5** we demonstrate precise placement of SWNTs in transistor channels. This approach became possible due to functionalization of the polymer with side chains containing thiols, to obtain chemical self-assembly of the selected s-SWNTs on gold electrodes. Network and single SWNT field-effect transistors with various channel lengths were fabricated by direct chemical self-assembly of the SWNTs/thiolated-polyfluorenes on substrates with lithographically defined electrodes. We show remarkable 100% yield for single SWNT devices demonstrating at the same time high performance and reproducibility over all devices. Noteworthy, the SWNTs assembled by mean of the thiol groups are stably anchored to the substrate and are resistant to external perturbation as sonication in organic solvents.