

Formation of the nanoscale contacts structure based on cross-junction of carbon nanotubes for the study of organic materials

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Using the dielectrophoresis method with unipolar rectangular pulses for the deposition of carbon nanotubes (CNTs), functionalized by COOH groups, single nanosized contacts based on a single-walled CNT and a functionalized single-walled CNT have been formed, the specific contact resistance of which, according to the estimate, was about $0.25 \mu\Omega\cdot\text{cm}^2$ or about $6 \text{ M}\Omega$ per one cross-junction of CNTs. The possible usage of the proposed technique for the nanoscale contacts formation based on the cross-junction of CNTs in various layers for the study of organic materials and charge transport in a nanoscale channel is considered.

Keywords: organic electronics, carbon nanotube, nanoscale contact, dielectrophoresis.

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1. Introduction

The study of charge transport in organic materials in conjunction with deposition methods, intermolecular interaction and contacts influence, is an actual task of organic electronics. Improving devices' characteristics and functionality is required to reveal the mechanisms that occur at the level of individual molecules and their functional groups. To this end, it is possible to use carbon nanotubes (CNTs) which form a transition from micro- to nanoscale, that makes it possible to develop principles of reducing the contact resistance [1], to study high-structured in the nanoscale organic materials [2], and to form nanoscale contacts [3]. However, existing technological approaches do not allow to form a large quantity of nanoscale contact structures for study different organic molecules and the contribution of the contact resistance to the characteristics of transistor structures based on them.

2. Materials and methods

We used an oxidized silicon substrate with a pre-deposited non-percolated array of single-walled CNTs (SWCNT), synthesized by the gas-phase method [4] over 20 s. Using group photolithography methods, the Au/Cr micro-contacts having opposite protrusions were formed. Then, SWCNTs were etched in an oxygen plasma using photoresist protective mask, and as a result, many structures were formed in which the SWCNTs had contact only with one of the micro-contacts (Fig. 1a,b). To deposit CNTs of the top layer and to form structures with individual contacts of CNT-CNT (Fig. 1c), deposition from a solution using COOH-functionalized SWCNTs (fSWCNTs) (Carbon Solutions, USA) was performed.

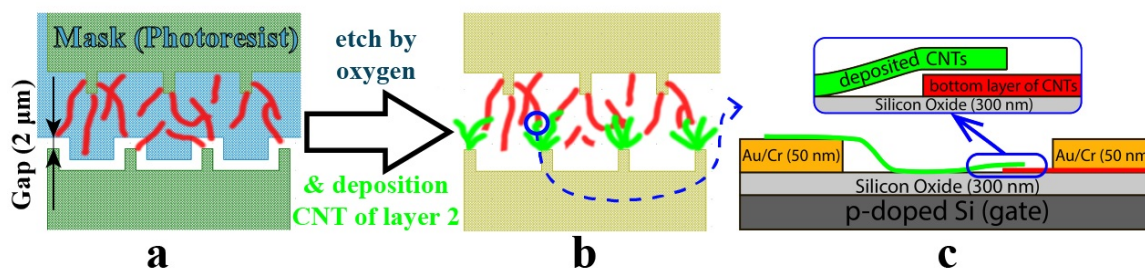


FIG. 1. Structures with micro-contacts before (a) and after (b) oxygen plasma etching and deposition of fSWCNTs as the top layer; SWCNTs form the bottom layer; cross section diagram of the nanocontact (c)

Before deposition, fSWCNTs dispersion was ultrasonically treated for 2 min and then centrifuged at $\sim 10,000$ g. Deposition was carried out by dielectrophoresis technique from the solution (volume $\sim 0.5 \mu\text{L}$ per iteration) with a substrate heated to 60°C , and nanoscale contacts were formed as the cross-junction of CNT between two layers (Fig. 1c). As a solvent, isopropanol (IP), N-methylpyrrolidone (NMP), cyclopentanone (CP) were chosen [5]. It was found that NMP has a very low evaporation rate and resistance, which led to the destruction of microcontacts due to the high current density and the absence of CNTs in the gap. IP had a low colloid stability time, which did not allow centrifugation. CP had a high evaporation rate ($0.01 \mu\text{L/s}$), a long colloid stability time (~ 3 h) and low conductivity, and was selected as the optimal solvent. Based on the topography obtained by the atomic force microscopy (AFM), we found optimal parameters of fSWCNTs solution, which provide the formation of single contacts of SWCNT-fSWCNT: concentration was $1 \mu\text{g/mL}$ or optical transparency 98 % in comparison with pure CP. So, the grid of fSWCNTs (length of separate fSWCNT $\sim 2 \mu\text{m}$) was formed.

3. Results and discussion

Several depositions of fSWCNTs from CP by dielectrophoresis using unipolar rectangular pulses (pulse time 5, 10 and 250 ms with period of 4 times longer than pulse time, amplitude 10 V) were carried out. The positive potential was applied to the contact without CNTs. This technique allows us to deposit fSWCNTs predominantly near one of the micro-contacts (see lower contact in Fig. 2a), preserving the edge of the second micro-contact practically clean (with a significantly lower density of fSWCNTs). At the ends of the nanotubes of the bottom layer, fields with a strength of more than $5 \cdot 10^6$ V/m were formed, however, according to the results of the AFM study, the deposition of the fSWCNTs was determined by the mean field at the microscale, i.e. $0.7 \cdot 10^6$ V/m, and it was not revealed the influence of localization of the field on the CNT of the first (bottom) layer on the deposition process of CNTs of the second (top) layer. At a pulse time of 5 ms, deposition occurred slowly (channels with CNT-CNT contact was not formed even after several iterations) with the formation of a grid of SWCNTs only directly near the protrusions of the micro-contacts. But, at pulse time of 250 ms, the channels of the top layer fSWCNTs were formed too quickly, that formed shunting channel in $14 \mu\text{m}$ gap between metallization without participation of CNTs of the bottom layer as second nanocontacts (one iteration was sufficient). Thus, such deposition was unmanageable.

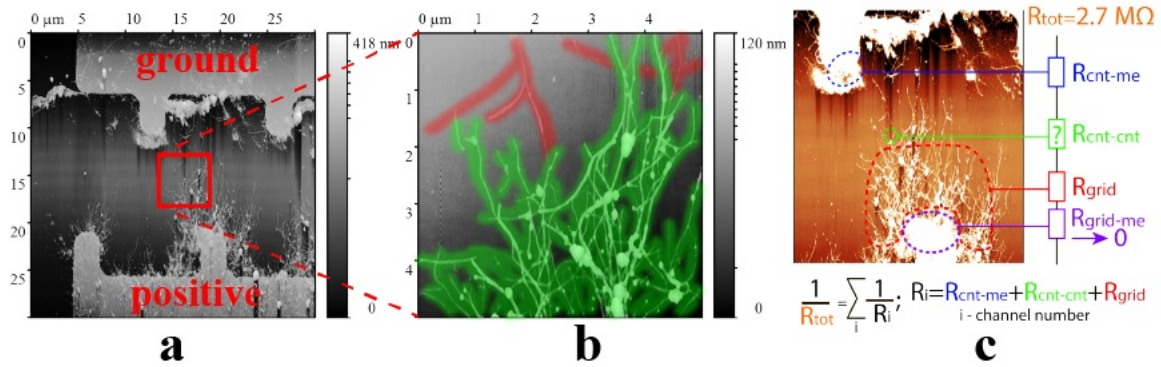


FIG. 2. AFM images of micro-contacts after dielectrophoretic deposition with pulse time of 10 ms (a) and amplitude of 10 V and increased contact site of SWCNT-fSWCNT (b). The red ones represent the SWCNTs of the previously deposited bottom layer, the green ones are fSWCNTs of the deposited top layer. An explanation of total resistance of the structure is given by the formula (c)

At a pulse time of 10 ms, single contacts of CNT-CNT as the cross-junction of CNTs between different layers were formed (Fig. 2a,b). The grid of deposited fSWCNTs was quite dense, but it grew gradually, forming single nanotubes at the edges, which formed contact. Based on the measured output current-voltage characteristic (CVC), the total resistance (R_{tot}) at $2.7 \text{ M}\Omega$ was estimated. The total resistance is determined the sum of the parallel channels (R_i), each of which includes: the resistance of SWCNT-metal (R_{cnt-me}), SWCNT-fSWCNT ($R_{cnt-cnt}$), and also the grid of deposited fSWCNT (R_{grid}). Therefore, to determine $R_{cnt-cnt}$, it was necessary to estimate each of them separately (Fig. 2c). The resistance of the SWCNT and the contact of fSWCNT grid with metal can be relied on to be negligibly small in comparison with other components. The estimation of the contact resistance of SWCNT-metal was carried out based of SEM images by counting the number of CNTs having contact to both

micro-contacts (before plasma etching operation) and output CVC of the structure and was for SWCNT-Cr/Au 600 k Ω for one contact or specific contact resistance 1.2 k $\Omega \cdot \mu\text{m}$ (recalculation on the SWCNT diameter ~ 2 nm), which is comparable with the literature data (~ 1 k $\Omega \cdot \mu\text{m}$ [6]). The estimation of the fSWCNT grid resistance of the top layer was carried out based on the results of analysis of fSWCNT films of similar density (using the four probe method) and was no more than 3 M Ω per square.

Thus, with considering the resistance of SWCNT-metal and also the resistance of the grid of the fSWCNT of the top layer, the resistance of SWCNT-fSWCNT nano-contact was 6.1 M Ω per one pair of CNTs or specific contact resistance 0.25 $\mu\Omega \cdot \text{cm}^2$ (with a SWCNT diameter of 2 nm), which agrees with the literary data, in particular, the contact resistance between a semiconductor and a metal CNTs (similar to the contact obtained in this work due to the use of fSWCNT having functional groups and SWCNT) was ~ 8 M Ω per one pair [7]). The proposed method of nano-contact formation allows using a cluster of organic molecules or their layer that can be formed before deposition of top layer CNTs for the formation of nanoscale OFET and studying its characteristics and using different molecules.

4. Conclusion

Thus, a technique for the formation of nanoscale contacts based on CNTs with the possibility of forming and studying molecular layers was proposed, and the contact resistance of fSWCNT-SWCNT was estimated with consideration of structural features, which should be useful for the study of charge transport in CNT-molecule-CNT structures.

Acknowledgements

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