# NOVEL FIELD-EFFECT CONTROLLED SINGLE-WALLED CARBON NANOTUBE NETWORK DEVICES FOR BIOMEDICAL SENSOR APPLICATIONS

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Keywords: Carbon nanotube (CNT), carbon nanotube field-effect sensor (CNTFES), carbon nanotube field-effect transistor (CNTFET), functionalization, virus-detection, integrated circuit, CMOS, hybrid CNT-CMOS integrated circuit, atomic force microscopy (AFM).

Abstract: In this position paper we propose a novel method for the realization of carbon nanotube field-effect sensors (CNTFESs) which will most likely have a strong impact on the next-generation of sensors. CNTFESs are ideally suitable for biomedical sensor applications due to their excellent inherent properties such as ultra small size, high specific surface area and extremely high sensitivity. CNTFESs are based on carbon nanotube field-effect transistors (CNTFETs) which are optimized for sensor applications. We have succeeded to develop a simple, reproducible fabrication process to grow individual CNTs and CNT-networks directly within the specified device area. No tedious manual manipulation and alignment of the CNTs is necessary. Electrical results of the fabricated fully functional CNTFETs are presented and the use of these devices as single-walled CNT-based field-effect controlled sensors for virus detection is discussed.

## 1 INTRODUCTION

Carbon nanotubes (CNTs) are hollow cylinders of graphene with a diameter of approximately 1 nm and lengths up to 100 µm. Multi-walled carbon nanotubes (MWNTs) consist of several concentrically arranged cylinders of graphene and were observed for the first time in 1991 (Iijima 1991). MWNTs are always metallic with very good conductivity. Single-walled carbon nanotubes (SWNTs), however, can be either metallic (m-SWNTs) or semiconducting (s-SWNTs) depending on the arrangement of the carbon atoms within the hexagonal network, i.e. their chirality.

Since 1998 (Martel 1998; Bezryadin 1998) it is known that s-SWNTs can be used to realize carbon nanotube field-effect transistors (CNTFETs) which are promising candidates for future nanoelectronic applications to replace Si-CMOS. Furthermore, only a change in the charge state is needed to alter the device characteristics via the field effect (i.e. just by the presence of the charge and not via current flow), so that extremely sensitive sensors are feasible, i.e. carbon nanotube field-effect sensors (CNTFESs).

In addition, the inner and outer surface of the single-walled CNT is equal to the whole tube itself and thus the CNTFES will be extremely sensitive to the immediate environment, i.e. ideally suited for biomedical sensor applications. In fact, excellent electronic response properties of CNTFETs to their chemical (Someya 2003) and biological (Staii 2005) environments have been demonstrated already. The response times of CNT-sensors are at least one order of magnitude faster than those based on solid-state sensors. CNT-based nanosensors have the advantages that they are thousands of times smaller than even MEMS sensors and consume much less power. Therefore, CNT-based nano-sensors are highly suitable as implantable sensors. Apart from their small size, semiconducting SWNTs operate at room temperature with a sensitivity as high as $10^3$ (Kong 2000). This enables them to perform better in many of the biomedical sensing applications.

Currently CNTFETs and CNTFESs are fabricated and investigated by several research groups. However, the fabrication processes used are often complicated, including both separate growth (Barreiro 2006) and tedious manual manipulation of

Schwalke U. (2008).
NOVEL FIELD-EFFECT CONTROLLED SINGLE-WALLED CARBON NANOTUBE NETWORK DEVICES FOR BIOMEDICAL SENSOR APPLICATIONS.
In *Proceedings of the First International Conference on Biomedical Electronics and Devices*, pages 99-102
DOI: 10.5220/0001055900990102

the CNTs (Kong 200; Someya 2003; Staii 2005). Obviously, commercial large scale integration remains a major challenge to the realization of CNT-based nanoelectronics and nanosensor technology as well.

At our institute we have developed a novel process to overcome the limitations of manual fabrication of CNTFETs and hence CNTFESs as well (Rispal 2006; Rispal 2007; Schwalke 2007). Our group has succeeded to develop a simple, reproducible fabrication process to grow individual SWNTs and SWNT networks as wells in order to fabricate fully functional CNTFETs and single-walled CNT-based field-effect controlled sensors.

In this position paper we will first present a brief summary of our research results on CNTFETs and subsequently discuss the use of this technology for possible biomedical CNT-based sensor applications.

# 2 RESULTS AND DISCUSSION

## 2.1 CNTFET & CNTFES Fabrication

The process is based on chemical-vapor-deposition (CVD) growth of CNTs using an aluminum/nickel ‘sacrificial’ catalyst which transforms itself after CNT growth into a high-k dielectric (i.e. $Al_xO_y$) covered with dispersed Ni-nanoclusters (Rispal 2007). SWNTs are grown uniformly across the wafer surface and subsequently contacted with palladium for S/D contacts and the Si-substrate acts as a gate electrode as illustrated in Fig. 1. The process contains neither complicated manipulations of the SWNTs nor multi-step lithography and is Si-CMOS compatible. We choose the in-situ growth method because it appears the most practical approach for future use in high-volume fabrication of advanced integrated nano-sensors at low cost.

For the development of this novel process we have extensively used atomic force microscopy (AFM) for process control and to optimize the CNTFET fabrication technology as well. The role of the Al/Ni films as “sacrificial” catalyst to stimulate SWNT growth is evident from the AFM images of Fig. 2 where the SWNTs always start to grow from a Ni-cluster and extend on the $SiO_2$. With topographic AFM the SWNTs with a diameter of approximately 1 - 2 nm are clearly detectable on smooth thermally grown $SiO_2$. Examples of simple CNT network structures are shown in Fig. 3.

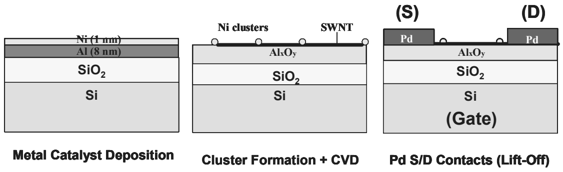


Figure 1: Process flow of CNTFET and CNTFES fabrication based on CVD with sacrificial catalyst.

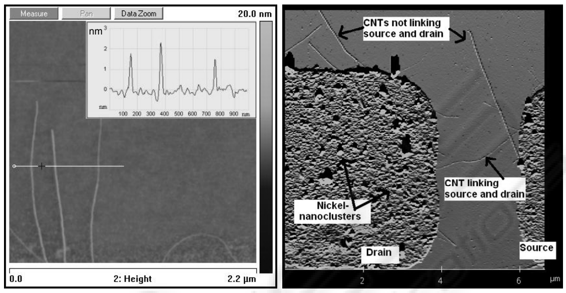


Figure 2: AFM scan of SWNTs with a diameter of approximately 1 to 2 nm on test structure (left). Top view of CNTFET/CNTFES with CNT connecting source and drain electrodes (right).

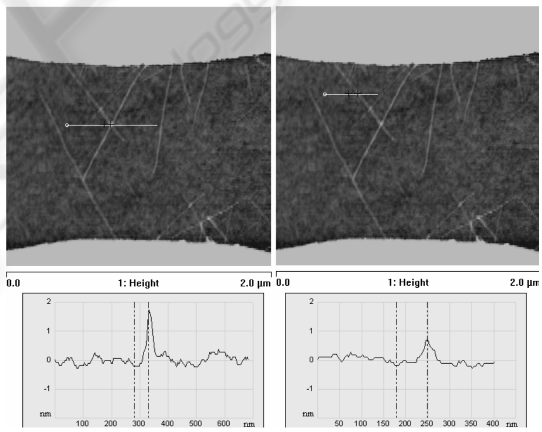


Figure 3: Example of CNT network structures with cross-over points.

## 2.2 Electrical CNTFET Device Characteristics

Once the electrical connection with the S/D contacts is established, the electrical characteristics of the CNTFETs can be obtained as shown in Fig. 4. In a CNTFET the electric field applied via the gate electrode modulates the charge carrier density in the nanotube and thus the current between the source (S) and drain (D) electrodes. Figure 4 shows the measured drain-current (Ids) as a function of the gate voltage (Vgs) which is swept between positive and negative values. Our fabricated devices are fully functional and the drain-current is well controlled by the gate voltage. Similar to conventional MOSFETs, the CNTFET device can be properly turned on and off. In fact, the on/off current ratio is in the $10^5$ range and exceeds the values of previously published “hand made” CNTFETs (Martel 1998; Bezryadin 1998). The transistor characteristic is unipolar and PMOS-like, i.e. a negative gate bias is required for turn-on.

The gate controlled drain current shown in Fig. 4 exhibits a strong hysteresis effect which is well reproducible. It has been found (Rispal 2007) that the hysteresis is caused by trapped charges and the related charge transfer at the interface between the gate dielectric and s-SWNT. With respect to CNT-sensor applications, the hysteresis effect confirms that any attached charges will have clearly detectable signatures on the device characteristics of

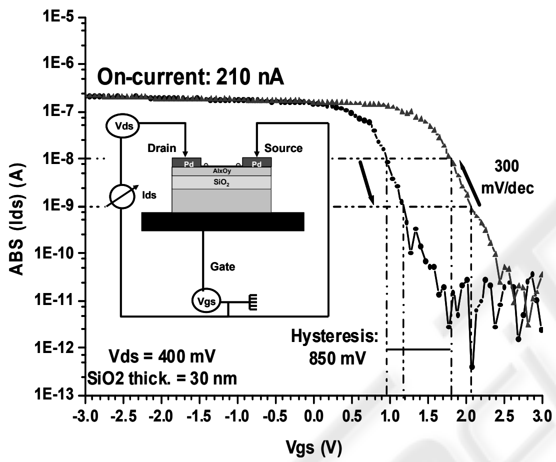


Figure 4: Measured transfer characteristics of fabricated CNTFET device structure. In this example the CNTFET contains just one s-SWNT. Device characteristics of CNTFETs containing multiple SWNTs (CNT-network) are similar, except for the increased drain current drive (Ids) proportional to the number of SWNTs in parallel.

CNTFETs. Since only the change in the charging state will be needed to alter the device characteristics via the field effect, extremely sensitive sensors are feasible.

These CNTFET devices form the basis of the technology platform of the proposed nano-sensors for biomedical applications.

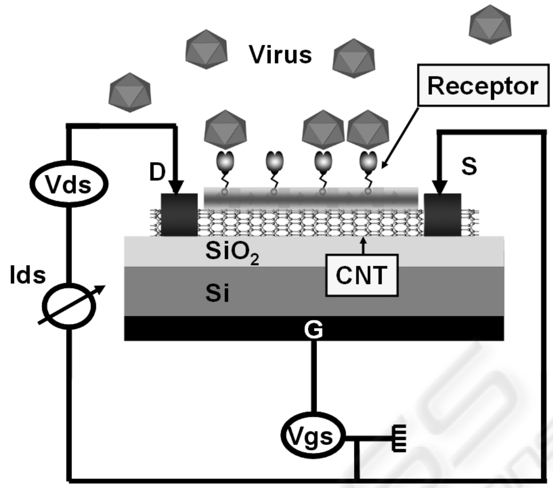


Figure 5: Illustration of proposed CNTFET-sensor for virus detection. The semiconducting single-walled CNT is functionalized with a suitable receptor to allow selective bonding via its protein. Extremely sensitive sensors for virus detection are feasible, since any change in the charging state introduced by the virus will alter the device characteristics via the field-effect.

# 3 PROPOSAL: BIOMEDICAL CNTFES

Taking advantage of the above mentioned hysteresis effect which we observe in our CNTFET devices, extremely sensitive nano-sensors (i.e. CNTFES) well suitable for biomedical applications can be realized. For example, the detection and identification of single viral particles may be possible using functionalized CNTFETs as sensors as illustrated in Fig. 5: The binding of a virus to a suitably functionalized s-SWNT will measurably affect the gate-dependent electrical current-voltage characteristics of the s-SWNT via charge transfer between the CNT and the virus. The virus detection is thus performed electronically via the CNTFET (cf. Fig. 4) which will alter its electrical device characteristics in presence of a virus. The sensitivity can be enhanced further by using CNT-networks (cf. Fig. 3) or array structures with multiple SWNTs. Furthermore, complete electronic integrated sensor circuits based on hybrid CNT-CMOS technology are envisioned which will perform data analysis on-chip (smart biosensors).

However, the main challenge for the realization of this biomedical sensor will be the proper functionalization of the CNT in order to be highly selective to the desired type of virus. This knowledge is outside of the scope of our own expertise (nanoelectronics). For a successful realization of these biomedical nano-sensors additional expertise from the biochemical and biomedical area is needed through collaborations with experts from the respective fields via research projects (e.g. EU FP7). In these projects we will provide the CNTFET-sensor devices and will be able to perform all necessary electrical characterization.

## 4 CONCLUSIONS

In this position paper we have proposed a novel method for the fabrication of carbon nanotube field-effect sensors (CNTFESs). These nano-sensors are ideally suitable for biomedical sensor applications due to their excellent inherent properties such as ultra small size, high specific surface area and extremely high sensitivity. Results have been presented on the novel fabrication process to grow individual CNTs and CNT-networks directly within the specified device area. This is the most practical approach for future use in high-volume fabrication of advanced integrated nano-sensors at low cost since tedious manual manipulations and alignment procedures of CNTs are obsolete. As a proof of concept electrical results on the fabricated fully functional CNTFETs suitable for sensor applications have been presented.

We are offering the biomedical device community our CNT-sensor technology in order to realize next-generation of nano-sensors within a joint project and to evaluate their potential in biomedical applications.

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