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To cite this article: S Soliveres et al 2009 J. Phys.: Conf. Ser. 193 012117

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Simulation of transport and $1/f$ noise in carbon nanotube films

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Abstract. In this paper we present a simulator for electrical properties of carbon nanotube film field-effect transistors. The simulator, based on carbon nanotube physics uses Landauer formalism and Poisson equation. The total film is described as an electrical network. A modified nodal analysis provides DC and noise characteristics. These simulations are in good agreement with experimental results.

1. Introduction

The properties of an individual nanotube make it interesting to use in microelectronic as transistor (CNFET). If the fabrications of high quality and reproducible CNFETs remains a difficult challenge, sensor applications using large quantities of CNTs are already available. The sensors consist of field-effect transistors based on films of CNTs arranged randomly. Although transport properties in individual nanotube have been intensively studied, little is known about structures with large quantities of CNTs.

The material consists of a large quantity of nanotubes arranged randomly. The first studies have shown that nanotube devices exhibit linear current-voltage characteristics and a large $1/f$ noise component. Collins et al have observed that this $1/f$ noise level appears to be proportional to the device resistance for individual NTs, films and mats that are CNT random networks [1]. Snow et al have measured the noise in films and have shown empirically that the noise appears to be proportional to the resistance and nearly inversely proportional to the film’s lengths [2]. This length dependence has not been observed in individual NTs, whether in the case of diffusive or ballistic transport, and appears to be specific to NT macrostructures. We have shown in an experimental paper that this length dependence is explained if we consider the structures as percolating networks [3]. In such a structure, CNT are links which are connected to form a path between two electrodes.

In this paper, we present an electrical simulator which allows to reproduce experiment and to predict the behaviour of noise and conduction in CNTs films and transistors.

2. Theory and modelling

2.1. Theory
Experiments have shown that nanotube films seem to behave as a small band gap semiconductor (sc) with p-type conduction. However, it’s not possible to describe a NT film as a crystalline
semiconductor compound. Due to the absence of covalent bond and to the cylinder nature of NTs, there is a weak coupling between NTs. Moreover the fact that CNTs can be described by links in a percolating network shows that NTs conserve their individual properties in the network. Two microscopic charge transport mechanisms occur in the film: the transport along nanotube themselves and the transport between crossed nanotubes. Considering the large mean free path in CNTs and the weak coupling between NTs, we assume that the contacts between NTs dominate the transport through the film.

2.2. Model

In order to get a microscopic understanding of the transport phenomenon, we have developed a simulator for the electrical properties of CNTs films. Nanotubes are set randomly on a surface and wide electrodes are defined to form source and drain with a low contact resistance (figure 1). In the network, we assume that the resistance of the intrinsic NT is negligible compare to NT junction. Thus we can draw an electrical equivalent circuit where nanotubes are wire of constant potential and resistance between tubes are due to junction resistances (figure 1). The tubes potential are computed using a modified nodal analysis (MNA). By this way the computational effort is hugely reduced for high tube densities because the matrix dimension depends on the number of tubes and not on the number of junctions and segments.

![Figure 1. A simple network and his circuit representation.](image)

Each intersection between tubes (metal/metal, metal/semiconductor or sc/sc) is modeled as a dipole with a dynamic resistance rc. The hopping from a tube to another is modeled as a perturbation in the transmission probabilities in the framework of Landauer formalism. Transmission probability \( T(E) \) depends on the nanotube charge \( \rho \) and on the energy barriers between nanotubes. Charge inside a tube is calculated self consistently with potential (Poisson equation) taking into account the gate voltage and the density of states \( D(E) \). The energy barrier is obtained by a first neighbor tight-binding calculation. From these values, the transmission probability is obtained by WKB approximation (to reduce computational time). In the considered experimental conditions each junction exhibits only 1/f noise source. The current noise spectral density is expressed as \( S_i(f) = K \frac{1}{f} \) with \( K = 10^{-10} r_c \) [4], and the total noise is calculated using the adjoint network method. The general algorithm is presented figure 2.a and the band diagram for a metal-sc junction is presented figure 2.b.
3. Simulation results

Device simulations are performed using the model presented previously. Figure 3 shows the simulated potential along a device for $V_{DS}=1$ V. For high CNTs densities the potential decreases linearly. For low CNTs densities, the potential drop is not homogeneous and there is dispersion in nanotube potentials. 1/f noise is more important in the nonhomogeneous parts and contributes mainly to the total noise.

Figure 4.a and 4.b present simulated conductivity and the noise coefficient $K$ for the different densities. The curves clearly exhibit the same behavior than experimental results [3], with similar exponents. Figure 5 presents a simulation of the drain current versus gate voltage for a CNT film composed of semiconductor nanotubes only. It indicates that transistors with very good $I_{ON}/I_{OFF}$ ratio could be competitive if it were possible to sort metallic and semiconductors nanotubes.

Figure 2. (a) General algorithm. (b) Band diagram for subbands around Fermi level for a M-SC junction. In inset the density of states of nanotubes.

Figure 3. NT potentials along the film for a density (a) 125 NT/μm², (b) 25 NT/μm².
We have developed a simulator based on random generated CNT film. The physical description of NT-NT junction allows to simulate CNT-FET based on carbon nanotube film. The simulator describes the conduction and noise measurements and their variations with the CNT density. These simulations show that this type of transistors can present good performances for low cost electronic applications.

**Figure 4.** a: Simulated conductivity (o) and power law (-) versus the NT density. b: Simulated noise (o) coefficient and power law (-) versus the NT density. W/L=1μm/4μm.

**Figure 5.** Simulated current and noise coefficient versus the gate bias for a CNT film field-effect transistor, for 60 NT/μm². W/L=1/4μm.

### 4. Conclusion

We have developed a simulator based on random generated CNT film. The physical description of NT-NT junction allows to simulate CNT-FET based on carbon nanotube film. The simulator describes the conduction and noise measurements and their variations with the CNT density. These simulations show that this type of transistors can present good performances for low cost electronic applications.