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Low-Frequency Noise Spectroscopy at Nanoscale: Carbon Nanotube Materials and Devices

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1. Introduction

This section presents brief description of peculiarities of carbon materials and advantages of noise spectsroscopy for the study of unique carbon nanotubes (CNT) materials and devices. In general, carbon is truly an extraordinary material with physical structures spanning three dimensional (3D) graphite, two-dimensional (2D) graphene and zero-dimensional (0D) buckyballs or buckminster fullerine spheres. It is not surprising that the structural characteristics of carbon thus yield band diagrams displaying a diverse array of physical properties. When a 2D graphene sheet is rolled into a cylinder, a one-dimensional (1D) or quasi-1D form of carbon results, namely CNTs, which have been one of the most extensively studied materials since their discovery. A single rolled-up sheet of graphene results in a single-walled nanotube (SWNT) with a typical diameter of 1 – 2 nm. The rolling direction is characterized by a chiral index (n,m). Achiral zigzag $(n,0)$ and armchair (n,n) CNTs are distinguished from the rest (chiral CNTs). Armchair tubes are always metallic, while zigzag tubes can be semiconducting or metallic (Reich et al., 2004).

Multi-walled nanotubes (MWNTs) consist of concentric cylinders with an interlayer spacing of 0.3 – 0.4 nm, and diameters that are at least an order of magnitude larger than SWNTs, between 10 – 30 nm. CNTs have high elastic modulus, strength, show efficient conductivity of heat, exhibit high thermal and chemical stability, flexibility, low mass density, and unique electrical properties (metallic conductivity and semiconductivity) which makes them excellent candidates for nano-devices and polymer composite materials (Sánchez-Pomales et al., 2010; Service, 1998). At the same time the CNTs are extremely difficult to manage due to their low solubility in both aqueous and organic solvents, which restrict the extent of their applications. Therefore one of the main challenges is the need for the development of new functionalization chemistries that can increase the solubility of CNTs without altering their CNTs properties. Transport in the CNTs of molecular SW- and MWNT-field-effect transistors (FETs) is dominated by holes and, at room temperature, it appears to be diffusive (Martel et al., 1998). Using the gate electrode, the conductance of a SWNT-FET is modulated

by more than 5 orders of magnitude. An analysis of the transfer characteristics of the FETs suggests that the CNTs have a higher carrier density than graphite and a hole mobility comparable to heavily p-doped silicon. Large-diameter MWNTs show typically no gate effect, but structural deformations can modify their electronic structure sufficiently to allow FET behavior.

Carbon nanotubes are perfect candidates for advanced nanoelectronic devices, and they have demonstrated great potential in a wide range of applications, such as FETs (Tans et al., 1998; Martel et al., 1998), elementary logic circuits (Bachtold et al., 2001; Liu et al., 2001), chemical and bio-sensors (Collins et al., 2000; Kong et al., 2000; Nguyen et al., 2002; Snow et al., 2005), hydrogen storage (Dillon et al., 1997; Yao et al., 2010), robust noise modulators for nonlinear systems (Kawahara et al., 2010).

While the noise is usually regarded as an undesirable property for applications, the fluctuation phenomenon in itself contains important information about the material and may be utilized as a valuable probe to characterize nanostructures. Nanotube based devices have been shown to exhibit very significant current fluctuations in the low-frequency (LF) regime (Collins et al., 2000), which may present serious limitations for device performance and applicability, e.g., the threshold voltage of a transistor and the detection sensitivity of a several type sensors. Excess noise above the unavoidable thermal Nyquist level, is a recognized barrier to practical, nanometer scale devices since it usually increases dramatically as dimensions shrink (Hooge, 1969). This large value of excess noise is not surprising and shows that the electrical current in nanotubes is transmitted through surface atoms and is easily perturbed by local charge fluctuations. The magnitude of this noise is an important consideration in assessing the potential of CNTs for electronic and sensor applications. Investigations of SWNT devices show that devices with similar resistances but with different sizes exhibit a systematic variation in the magnitude of $1/f$-noise (Snow et al., 2004). In particular, it is observe that the level of $1/f$-noise in large-area devices is significantly less than the level of noise in small-area devices of comparable resistance.

Both equilibrium and nonequilibrium fluctuations of a particular atom's location, for example, gain importance as conduction paths reduced to atomic dimensions. CNTs, being covalently bonded materials, might be less susceptible to such fluctuations. Furthermore, the strong carbon–carbon bonds which form the CNT should not be subject to electromigration or defect propagation, two of the most important noise mechanisms in standard metal films and wires (Dutta & Horn, 1981). Since nanomaterials have been used for transport studies it has been frequently observed that their electrical characteristics showed substantial LF current fluctuations. In the case of CNTs those fluctuations classified as $1/f$-type (Collins et al., 2000; Roschier et al., 2001; Snow et al, 2004; Ishigami et al., 2006; Lin et al 2006; Liu et al., 2006a, 2006b).

The first studies of CNT devices have shown that the $1/f$-noise is much more pronounced than in conventional bulk devices and this may seriously limit the potential of CNTs for applications in electronics. Later some of the investigations demonstrated a very promising noise level at a very small current regime. The noise characteristics may be used to reveal important information concerning transport phenomena of CNT based devices in different conditions and regimes.

In-depth LF noise studies of CNT transistors and resistors can identify device imperfections such as charge trapping centers along the CNT as well as its interface with gate oxide. Large amplitudes of LF noise increase the minimum detectable signal

magnitude at low frequencies. There are reports on electronic LF noise in a metallic CNT (Fischer et al., 1997; Singh & Ghosh, 2008), CNT ropes (Collins et al., 2000; Roche et al., 2002), networks (Collins et al., 2000; Snow et al, 2004; Lin et al 2006), individual s-CNTs (Ishigami et al., 2006).

Usually CNT structures are fabricated in a FET configuration to study their transport properties. Despite the progress in CNT- FET technology, transport phenomena are still under debate. Noise spectroscopy is a powerful method for studying the transport properties, performance and reliability of material and devices, including FETs based on CNTs. It should be noted that many standard material characterization methods such as the utilization of the Hall effect, measurements of the photoconductivity and the capacitance-voltage characteristics became ineffective for nanoscaled materials and devices. At the same time, noise spectroscopy is an even more sensitive method for studying the influence of scaling on objects down to the nanoscale. Usually LF excess noise, which is registered above the thermal Nyquist noise level, increases as the dimensions shrink. The main factor in conventional materials is an increased surface-to-volume ratio due to defect surface states which are usually closer to the conducting channel.

In this review we describe noise properties of carbon nanotube based materials and devices. After brief introduction in peculiarities of transport and noise properties of CNTs we describe main noise components and theoretical models of the flicker noise directly related with conductivity of the materials. Then we review noise properties of individual CNT-based structures, which are considered to be the best from a nanoscale fundamental studies point of view. They have a cylindrically perfectly ordered shape almost without defects in the structure. We will show that the noise characteristics of CNTs are competitive to conventional materials, but many new features of transport can be revealed as a result of the nanoscale sizes of the nanotube. These objects are good for the modeling of the physical properties of any new kind of materials at the nanoscale. Then we will continue to describe the properties of carbon nanotube thin films. These structures, tunable at the nanoscale but still exhibiting quasi-bulk properties, are promising since they are flexible for different kinds of applications such as high-speed or impedance matched devices. In spite of the progress in their production technology the noise level is still high due to the excess noise produced as a result of fluctuations in the tube-tube junctions. Next we will describe noise properties in parallel aligned nanotube channels. The structures demonstrated reduced noise properties. We will discuss our efforts to improve the properties of the CNT-FETs using gamma radiation treatment. Our analysis shows that the difference in output characteristics of the FETs before and after small doses of gamma radiation treatment is due to a reduced contribution to the total current parallel to the nanotube resistance. It should be emphasized that the transconductance of the CNT-FETs and level of noise did not change strongly after the treatment with a dose of 1×10^4 Gy and 2×10^4 Gy. Moreover our results show that active gamma-radiation treatment can improve the transport and noise properties of CNT-FETs at a small optimal dose. The radiation treatment was found to decrease the influence of parasitic conduction channels on transport characteristics of the device. The Hooge parameters obtained are comparable to typical values obtained for conventional semiconductors. After that we will briefly give an overview on results of transport studies on CNT-based structures using shot noise. Finally we will draw the main conclusions and give a short outlook for the potential of noise spectroscopy as the basis for novel technology development.

2. Theoretical predictions of noise properties

This chapter presents the peculiarities and possibilities of Noise Spectroscopy (NS) for study CNT materials and devices at nanoscale. Usually quality and reliability of various electronic devices are correlated with their LF noise. The basic idea of NS is to treat the correlation links present in sequences of different irregularities, such as several interfaces, tube-tube junctions, spikes, "jumps", and discontinuities in derivatives of different orders, on all levels of the spatiotemporal hierarchy of the system under study as main information carriers. The tools to extract and analyze the information are power spectra or noise spectral density (NSD). Generally, several types of noise components can be separately analysed in solid state materials and devices. The components are following: the thermal noise, shot noise and excess noise (Ziel, 1986). The latter may be represented by random telegraph signal noise, generation-recombination noise, as well as the 1/f -type flicker noise dependent on physical origin of the processes in the system.

- Thermal noise, also known as Nyquist one, is result of random Brownian motion of the charge carriers in a resistor R at definite temperature T, shows independent on frequency, f, spectral power: $S_V = 4kTR$, where $k = 1.38 \times 10^{-23}$ J K^{-1} is the Boltzman constant. R can be found from measured I-V characteristic of the resistor as $R = dV/dI$, where V is the applied voltage, I is the current through the sample. The spectral density does not dependent on the current through the resistor and on material of the resistor. At the same time it can be used to analyse the effective electron temperature.

- Shot noise, which is also white in nature, arises from discrete transport characteristic of charge carrier, e: $S_V = 2eI$. Usually the shot noise became registered at low temperature, when the thermal noise is decreased and statistical fluctuations due to finite number of particles can be detected.

- Random telegraph signal (RTS) noise consists of sudden step-like fluctuations in time caused by transitions between two or more levels. Two level RTS caused by single defect results in Lorentzian noise spectrum.

- Generation-Recombination (G-R) noise is result of individual trapping-detrapping process of charge carriers to and from the traps with spectral density for definite G-R component described by Lorentzian spectrum: $S_V(\omega) \propto \tau/\left[1+(\omega\tau)^2\right]$, where τ is the time constant of process (carrier lifetime, etc), $\omega = 2\pi f$.

- Flicker noise or 1/f -noise named due to characteristic spectral density dependence on frequency: $S_V(f) \propto 1/f^\gamma$, where γ is nearly 1 as for metallic as well as semiconductor carbon nanotubes. It is now established that 1/f-noise is characteristic of any kind of system, starting from single molecule to biological, physical, chemical systems and other system, including music, finance, and economy areas of research. This noise component involves a number of fluctuation processes with a time constant distribution composing 1/f dependence in noise spectra.

Usually noise spectra of FETs measured at room temperature can be described by three noise components. Fig. 1 shows typical noise spectrum, describing summarized noise, shown in red, as $S_V(f) = flicker + (generation - recombination) + thermal$:

$$S_V(f) = \frac{A}{f^\alpha} + \sum_i \frac{B_i}{1 + (2\pi f \tau_i)^2} + 4\mathrm{k}TR \, , \tag{1}$$

where, A is the amplitude of $1/f$-noise at $f = 1\,\mathrm{Hz}$, τ_i is the time constant i-component of the G-R-process, B_i is the amplitude of i-component of the G-R noise.

In this review we concentrate on flicker noise as dominant type of low-frequency fluctuations in carbon nanotube materials and devices at room temperature. In addition, this type of noise is directly related with conductivity of the structure. In this respect the noise is the most important as characteristic of transport regimes in the channel of the structure. Knowledge of the noise characteristics is important to characterize performance of nanotube based devices. Various researchers have predicted both large and small levels of $1/f$-noise in CNT transistors. From one point of view, the strong carbon–carbon bonds in a CNT should reduce the amount of ion motion, which is a suspected source of $1/f$-noise in other systems (Dutta & Horn, 1981). However, in CNTs every atom being a surface atom, and are thus susceptible to the influence of adsorbents (Collins et al., 2000). Additionally, due to the 1D electronic structure of the CNT, a local defect must globally affect the current.
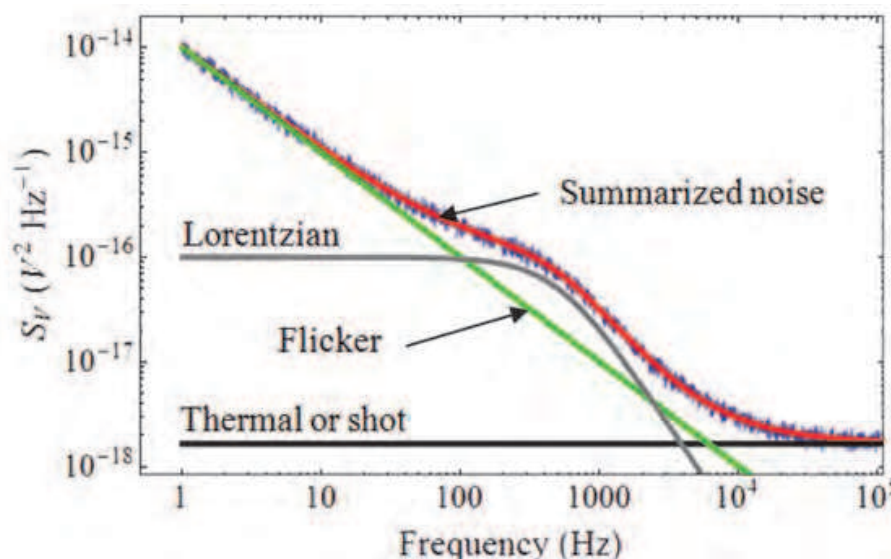

Fig. 1. Typical noise spectrum, measured at room temperature. Three noise components allow to describe LF noise spectra, S_V: flicker, G-R and thermal. It should be noted that the shot noise became registered at low temperature, when the thermal noise is decreased.

It is now accepted that $1/f$-noise is produced by fluctuations of sample conductance. In general, if diffusive transport is assumed, the conductance σ is proportional to both carrier mobility, μ, and carrier concentration, n:

$$\sigma = e\mu n . \qquad (2)$$

Therefore both components, n as well as μ, including their changes under the influence of external charge phenomena can contribute to $1/f$-noise. The contribution of such a component can be studied dependent on the operation regime, different kinds of external influence, the surrounding conditions, the contact to chemo- and biomolecules, including label-free identification at the single molecule level.

There are mainly two major theories for $1/f$-noise in these devices (Vandamme et al., 1994):

i.   McWhorter theory of number (Δn) fluctuations,
ii. Hooge theory of mobility ($\Delta\mu$) fluctuations.

The main physical difference between these two cases is the origin of the flicker noise. McWhorter theory predicts flicker noise to be a result of number fluctuations (Δn) of charge trapping by tunneling processes in surface or interface states (McWhorter, 1957). Later thermally activated processes were suggested by Dutta and Horn for explanation of 1/f noise as a result of fluctuations of time constant τ (Dutta et al., 1981). The temperature dependence of the noise is different for tunneling and thermally activated processes, therefore such models can be separately applied. F.N. Hooge proposed that 1/f -noise is not a surface effect and it is essentially a bulk phenomenon as a result of bulk carriers mobility fluctuations ($\Delta\mu$) due to lattice scattering (Hooge, 1969; Hooge et al., 1981). Investigating metal films he found an empirical relation for 1/f -noise in form:

$$S_i = \frac{\alpha_H I^2}{fN} , \tag{3}$$

where α_H is the Hooge's constant, related to the quality of the sample and defines the level of the low-frequency noise, which is dominated by the flicker noise; N is the total number of free carriers. However, Weissman later emphasized that flicker noise extending to very low-frequencies should have a long-term memory for the fluctuation process (Weissman, 1988). The question how lattice scattering provides a memory effect in the noise taking into account that the mean life time of the carriers is in the picoseconds range is still open. The model also can not explain the cases of deviation of the frequency exponent from unity. Therefore, to describe the noise peculiarities, a combination and modification of both models number (Δn) and mobility ($\Delta\mu$) applicable for many types of conventional FETs and other semiconductor devices are proposed (Hung et al., 1990; Mannik et al., 2008; Mihaila, 2004; Gasparyan et al., 2010). By studying the gate voltage dependence of the noise associated with source-drain current, the contributions coming from fluctuations of n and fluctuations of μ can be separated (Ghibaudo & Boutchacha, 2002). Models based on mobility fluctuations predict that α_H is independent of gate voltage, V_g, while $\alpha_H \propto 1/|V_g - V_{th}|$ in models based on number fluctuations (Vandamme et al., 1994). Here V_{th} is the threshold voltage. Such as, in the linear regime, $1/A \propto |V_g - V_{th}|$ if noise is due to mobility fluctuations and $1/A \propto |V_g - V_{th}|^2$ if noise is due to number fluctuations. In the case, when the amplitude is inversely proportional to the device length the noise is a property of the length-dependent resistance of the CNT and not the electronic contacts.

The ratio of electronic noise to device signal is expected to increase with decreasing size and is thus of concern in nanoscale devices. In addition, surface adsorbents (Hedouin & Rous, 2000) are expected to have increased influence on electronic noise as the surface to volume ratio increases. Hooge model suggests that noise is caused by independent scattering events of charge carriers, which lead to $1/N$ dependence (Hooge, 1969, 1994; Hooge et al., 1981). Tersoff has proposed an alternative model that assumes that the SWNT-FET is affected by random fluctuation of charge in its environment (Tersoff, 2007). In this "charge-noise model"

$$S_I \propto \left(\frac{dI}{dV_g} \right)^2 , \quad A \propto \left(\frac{d\ln I}{dV_g} \right)^2 . \tag{4}$$

The charge fluctuation noise model modified for the system of p-Si/SiO$_2$/Ta$_2$O$_5$/dendrimer/single-walled CNT/electrolyte bio-chemical sensors successfully used for the explanation of noise peculiarities (Gasparyan et al., 2011b).

The expected noise immunity of a covalently bonded system is in competition with the increased relative importance of individual atomic fluctuations in nanometer-sized junctions. This size scaling is incorporated in Hooge's empirical law:

$$S_I = A \frac{I^\beta}{f^\gamma} ,$$

(5)

which expresses the excess noise magnitude as :

$$A = \frac{\alpha_H}{N} ,$$

(6)

$\alpha_H = 0.002$ is a constant at T= 300K for most bulk metallic systems, and even extends to the $N = 1$ case at the tip of a scanning tunneling microscope. Dependence $\alpha(T)$ can vary as a result of sample preparation, material, defect density, and other effects (Hooge, 1994), therefore the temperature dependence of the Hooge factor may provide insight into the physical origin of the flicker noise.

3. Noise spectroscopy of transport phenomena of individual carbon nanotube FETs

Individual carbon nanotube FETs (Fig. 2) are the best modeling objects for study how noise and transport characteristics change at moving to real nanoscale ballistic devices. If the channel of the device is short compared to the inelastic scattering length, then wave properties with definite transmission factor describe the transport in quantum channel. At the same time the influence of contact interface properties is increased and most of the FETs operate as Schottky barrier (SB) devices. Moreover in CNT metal induced gap states are far less effective in pinning the Fremi level at nanotube-metal contact (Leonard et al., 2000) due to 1D geometry. The barrier height at interface between CNT and metal contact is strongly affected by the local work function of the interface materials and the device properties can be effectively tuned by external environment. As a result CNT FETs demonstrate unexpected behavior different from conventional planar devices (Heinze et al., 2003). The dependence of current NSD S_I (or A) on gate voltage (Lin et al., 2006; Ishigami et al., 2006; Briman et al., 2006), CNT length (Ishigami et al., 2006), the substrate on which the SWNT rests (Lin et al., 2007) has been discussed. The majority of these studies compare experimentally measured noise magnitudes in SWNT-FETs (Collins et al., 2000; Ishigami et al., 2006; Lin et al., 2007; Appenzeller et al., 2007) to the empirical Hooge model. It is shown that Hooge's empirical rule adequately describes the LF noise in semiconductor CNT-FETs with $\alpha_H = (9.3 \pm 0.4) \times 10^{-3}$ (Ishigami et al., 2006).

3.1 Investigation of influence of contact interfaces

In general, a detailed understanding of influence of contact interface on the noise properties is needed to optimize the signal-to-noise ratio (SNR) across the full operating range of the

FET. There are two main types of CNT-FETs that are being currently studied, differing by their current injection methods. CNT-FETs can be fabricated with Ohmic or Schottky contacts. The type of the contact determines the dominant mechanism of current transport and device output characteristics. CNT-FETs are mainly divided into Schottky barrier CNT-FETs (SBCNT-FETs) with metallic electrodes which form Schottky contacts and metal-oxide-semiconductor field-effect transistor (MOSFET)-like CNT-FETs with doped CNT electrodes which form Ohmic contacts. In SB-CNT-FETs, tunneling of electrons and holes from the potential barriers at the source and drain junctions constitutes the current (Tersoff, 2007). The barrier width is modulated by the application of gate voltage, and thus, the transconductance of the device is dependent on the gate voltage (Raychowdhury et al., 2006). A typical structure and the distribution of the potential energy on the channel are shown in Fig. 3. The gate voltage makes the barriers near the source/drain thinner and increases the tunneling current. A typical structure of the MOSFET-like CNT-FETs with 20 nm doped sections and its energy band diagram is shown in Fig. 4.

One of the important aspects of NT transistors is the ambipolarity or unipolarity of their current-voltage characteristics. SB-CNT-FETs exhibit strong ambipolar behavior. For high enough gate voltages the tunneling probability of electrons through the source Schottky barrier in the conduction band is high and for the low and negative gate voltages, a Schottky barrier is formed at the drain in valence band and tunneling of holes increases the current. The energy bands for low and high gate voltages and the Schottky barriers are shown in Fig. 3. However for MOSFET-like CNT-FETs only positive gate voltages because of lowering the barrier in the channel increase the current. The energy bands for low and high gate voltages and the potential barrier in the channel are shown in Fig. 4.
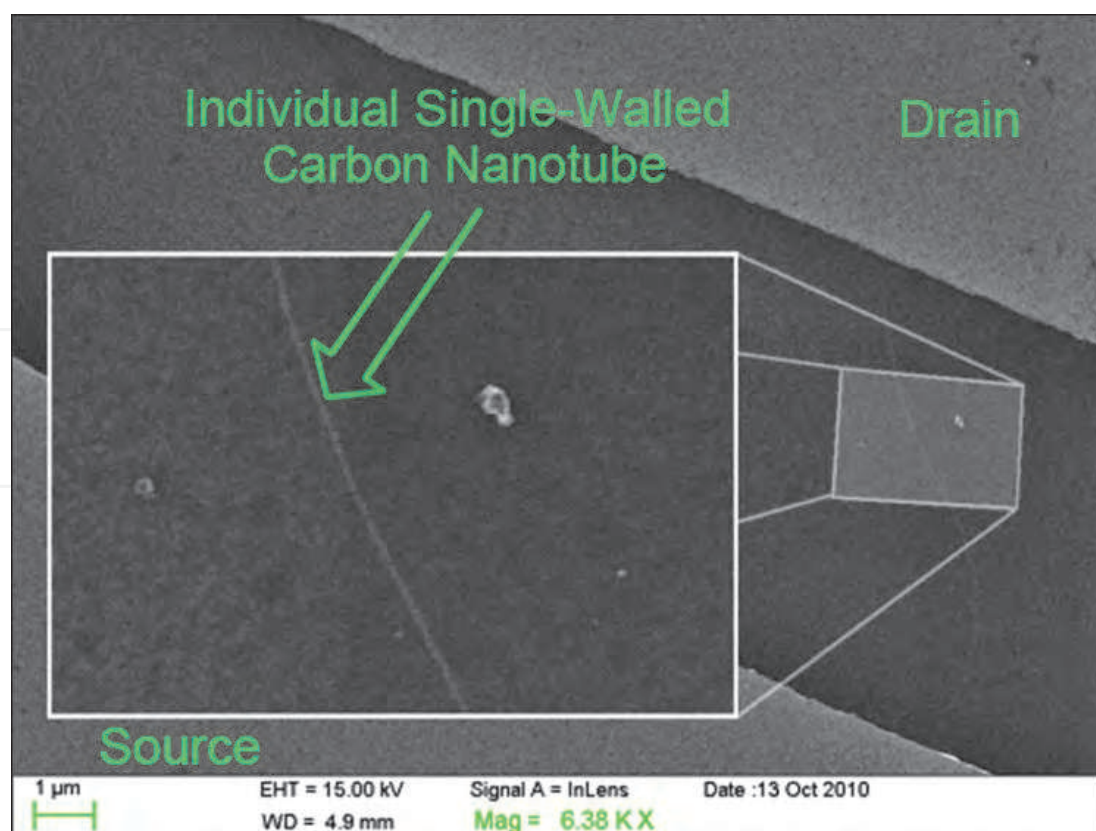

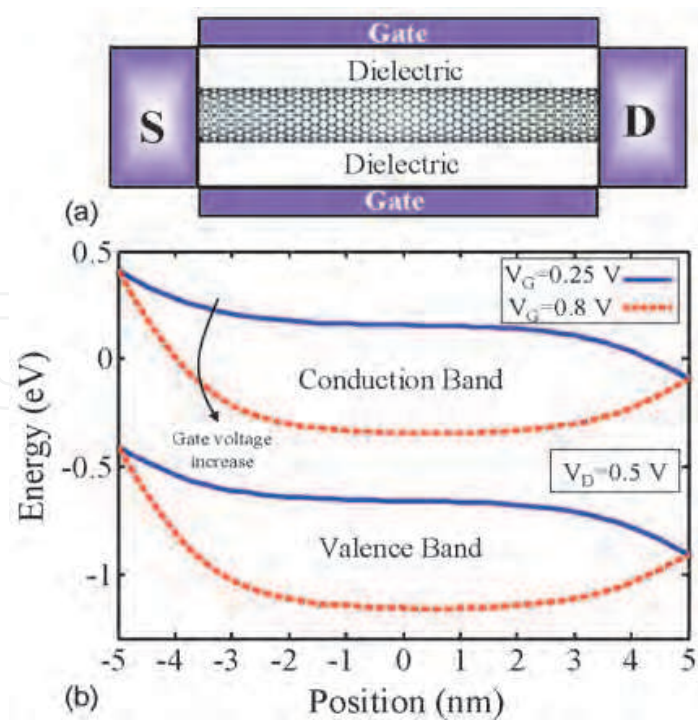Fig. 2. SEM image of typical a CNT-FET with back gate

Fig. 3. Schottky Barrier CNTFET, a) 2D cross section of the coaxial structure with intrinsic CNT as the channel and metal source/drain contacts, b) Energy band diagram. The metal Fermi level is taken to be at the midgap of the CNT (Kordrostami et al., 2010).
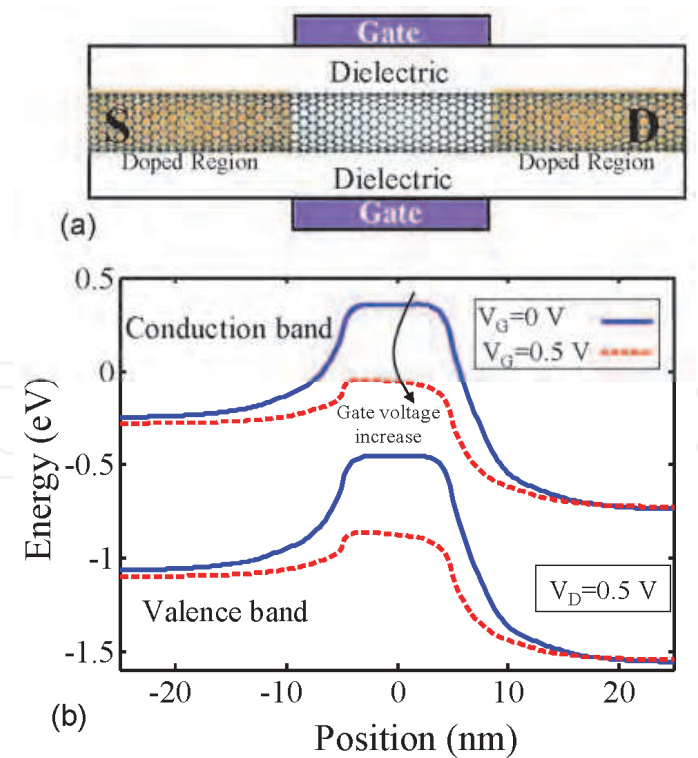

Fig. 4. MOSFET-like CNTFET, a) 2D cross section of the coaxial structure with intrinsic CNT as the channel and doped CNT sections as source/drain contacts, b) Energy band diagram (Kordrostami, et al., 2010).

Several studies suggest that CNT-FETs as Schottky-barrier transistors have a very large contact resistance at low bias related to a tunneling barrier which can be tuned with the gate voltage (Heinze et al., 2002). The results demonstrate that the device characteristics can be radically improved by tailoring the contact geometry. The charge redistribution through the interface, associated with the physics of band bending and its resulting depletion layers, and the possible occurrence of metal-induced gap states are expected to depend strongly on the relative positions of the Fermi level and band edges of the metal and CNT in contact (Tersoff, 1984). It has been shown in particular that various scaling laws, such as the length of the depletion layer as a function of doping fraction or the interface dipole, differ significantly in 1D from their 3D analogs (Heinze et al., 2005). Influence of doping on transport properties of electronic devices on the base of CNTs discussed by Charlier (Charlier et al., 2007). To demonstrate the N dependence and to evaluate the influence of scattering on the $1/f$-noise of NTs, in (Collins et al., 2000) fabricated two SB-CNT-FETs with very different channel lengths: $L \approx 500$ nm and 7 μm, which are denoted as short (S) and long (L) devices, respectively. To eliminate device-to-device variations, the two CNT-FETs are fabricated using one, single, long semiconducting CNT and share a common electrode as the source. The ratio of the noise amplitude $A_S/A_L \approx 10$ of the two devices is comparable to the inverse of the corresponding length ratio $L_S/L_L = 14$, consistent with $A \propto 1/N (\propto 1/L)$ behavior. Taking into account this length dependence, the CNT-FET resistance can be expressed as

$$R = R_{SB} + R_{diff} = R_{SB} + R_0 \frac{L}{\lambda}, \quad R_0 \equiv \frac{h}{4e^2}, \tag{7}$$

where λ is the electron mean-free-path in the CNT and R_{SB} and R_{diff} are the resistance contributions due to the contact Schottky barriers and the scattering within the CNT channel, respectively, R_0 is the theoretical tube resistance at the ballistic limit $(\sim 6.5 k\Omega)$. Although it has been suggested that the $1/f$-noise in bulk materials is induced by scattering with surface or/and bulk phonons (Mihaila, 2004; Gasparyan et al., 2010; Asriyan & Gasparyan, 2004; Asriyan et al., 2004; Melkonyan et al., 2003, 2005a, 2005b, 2006, 2007) and the same may be true for CNTs (Gasparyan et al., 2009, 2011; Mihaila, 2002) the agreement between A_S/A_L and L_S/L_L is striking and suggests that α_H in CNFETs is not substantially influenced by the presence of acoustic phonon scattering in the long channel device.

The noise amplitude of the CNT devices is related to the resistance of the device. A/R has been found to be varied from 10^{-11} to 10^{-9} for both metallic and semiconductor SWNT devices (Vijayaraghavan et al., 2006). While the current fluctuation generated by each trapping–detrapping centre takes the form of random telegraph signal (Liu et al., 2005), the superposition of such RTS noises with a wide distribution of switching time constants yields the $1/f$-noise spectrum. A RTS appears at a smaller absolute gate bias for a larger absolute drain-source bias in a CNT transistor (Roschier et al., 2001). The noise mechanism is attributed to a defect located in the drain side of the Schottky barrier CNT transistor with Ti/Au as contact material. It is noted that room temperature RTS is presented for both metallic and semiconductor CNT. By studying CNT devices with various diameters and contact metals, it is show that the ON-currents of CNFETs are governed by the heights of

the Schottky barriers at the metal/CNT interfaces. The current fluctuations are dominated by 1/f -noise at low-frequencies and correlate with the number of transport carriers in the device regardless of contact metal (Lin et al., 2007).

Sources of flicker noise in CNT-FET passivated using a high quality atomic layer deposited HfO$_2$ gate oxide have been reported (Kim et al., 2010). The measured 1/f -noise of the device stems from superposition of the excess noise in the Schottky barrier contacts and charge trapping – detrapping at CNT/oxide interface. Based on these results, a model for LF-noise in CNT-FETs is proposed and dominant mechanisms responsible for 1/f -noise in various device operation modes are discussed. Referring to energy-band diagrams Kim and co-authors roughly categorize the mechanism of carrier transport of the top-gate transistor as a function of biasing condition into two regimes (Kim et al., 2010):

i.   Schottky barrier modulation regime: in this regime carriers are controlled by the Schottky barriers between drain/CNT and source/CNT contacts. As the drain bias is increased, the Schottky barriers become thinner and help carriers to move into the channel by thermionic emission process. In this case the 1/f -noise is proportional to the square of drain current.

ii. Gate modulation regime: under small drain/source bias the depletion regions of the CNT due to Schottky barriers are short. Carriers that pass from contacts to the channel by thermionic emission are well-controlled by the height of the energy-band and are thus controlled by the gate voltage. Long CNT-FETs show gate modulation under a larger drain/source bias. The 1/f -noise of the FETs, mainly affected by the gate bias, is dominated by charge trapping-detrapping phenomena.

By examining devices with different switching mechanisms, carrier types, and channel lengths, it is shown that the 1/f -fluctuation level is correlated to the total number of transport carriers present in the system. However, the 1/f -noise level per carrier is not larger than that of most bulk conventional semiconductors, e.g., Si.

Study that evaluates the 1/f -noise in a ballistic, 1D system, i.e., an semiconductor CNT, as a function of metal contact material and sample geometry in a FET layout and in nanoscale ballistic transistors presented in (Appenzeller et al., 2007; Lin et al., 2007). The distance between the source and drain electrode is around $L = 600$ nm for transistors. The 1/f -noise amplitude is obtained using $A = S_I f / I^2$. Based on experimental results presented in (Lee et al., 2006) $A_n = 10^{-10} R_0 / L$ were used for the 1/f -noise amplitude of individual NTs (L is the length and expressed in microns, $R_0 = 6.5 \text{k}\Omega$ is the minimum resistance in the absence of disorder). Based on experimental data a relationship $A_n = a r_n$ was assumed with $a = 10^{-10} \Omega^{-1}$. The simulation results clearly indicate that $A/R \sim L^\alpha$ is a strong function of device length with a critical exponent $\alpha = -1.3$ (for $8 < L < 20 \ \mu$m).

Investigations of LF current fluctuations of nanodevices consisting of one single semiconducting NT demonstrate that the noise amplitude A also increases monotonically with the device resistance R , with an A/R ratio that lies between 2×10^{-10} and $2 \times 10^{-9} \Omega^{-1}$ (Lin et al., 2006). Results of (Lin et al., 2006) present strong evidence that the gate-dependent 1/f -noise observed in CNTs for 1D systems exhibiting quasi-ballistic transport behavior is modulated by the total number of transport carriers in the channel, and the fluctuation mechanism is independent of the carrier type, i.e., electrons or holes. Furthermore, the 1/f -noise parameter determined for the CNT-FETs that consist of unpurified CNTs is quite comparable to the value observed in most bulk systems.

Hence, the noise of CNT-FETs with short channel length will be more related to the contact geometry. This should be taken into account for developing CNT-FETs with ohmic contacts.

3.2 Dielectric-nanotube interaction and hysteresis phenomena

Charge trapping in the gate oxide n-FETs may cause LF-noise and threshold shifts (Wang et al., 2007). The 1/f -noise characteristics in such devices are determined by extrinsic factors arising from ambient conditions rather than by intrinsic properties of the CNT or the necessary interfaces (i.e. CNT – oxide interface and Schottky barrier contacts). Avalanche injection into oxide traps result in the hysteresis effect in the I-V characteristics of the CNT-FETs and allows the device to function as a non volatile memory cell (Radosalvljevic et al., 2002). There are mainly two major sources for 1/f -noise in these devices (Kim et al., 2010): the excess noise in Pd – CNT Schottky barrier leading to G – R noise in the space-charge region including metal – CNT interface and charge trapping – detrapping phenomena at the CNT/oxide interface. Under a small drain bias, the Schottky barriers do not influence the transport and carriers are modulated by local gate-biasing similar to a MOSFET in linear/triode regime. Current fluctuation in this mode of operation is due to trapping/detrapping processes involving interface traps and trapped charges in the oxide layer. According to Hooge's empirical law, the 1/f-current noise amplitude can be written as following.

In the linear region current NSD is modeled as:

$$S_I(f) = \frac{\alpha_H e \mu_{eff}}{f L^2} V_{sd} g_m (V_{sg} + V_{th}) \ , \tag{8}$$

in the saturation regime

$$S_I(f) = \frac{4 \alpha_H e g_m^2 \mu_{eff}}{9 f C_g L} \frac{V_{sg} + V_{th}}{1 + \lambda V_{sd}} \ , \tag{9}$$

where $C_g L (V_{sg} + V_{th})/e \equiv N$ is the total number of carriers in CNT-FET channel, C_g is the gate capacitance per unit length, L is the gate length, V_{sg} is the gate bias voltage, V_{th} is the threshold voltage, V_{sd} is the source/drain bias voltage, λ is the channel length modulation parameter, μ_{eff} is the effective carrier mobility.

The trapping–detrapping of carriers in the oxide changes the number of carriers in the channel and also varies the surface potential along the CNT. For the intramolecular CNT-FET the 1/f -noise spectral density has been measured for individual CNTs as a function of the direct current (DC) I_{DC} at room temperature. At $I_{DC} = 0$, the voltage noise is white and equals the expected value for thermal noise $4kRT = 2.1 \times 10^{-16}$ V²/Hz of the CNT, where $R = 12.6$ kΩ for this device (Postma et al., 2001). With increasing current, additional noise appears which exhibits 1/f -dependence. These two noise powers appear to add incoherently, i.e.

$$S_V = 4kTR + \frac{A V_{DC}^2}{f} \ . \tag{10}$$

The frequency dependence of the noise reveals two types of LF noise spectra. For the first type the noise spectrum is strictly $1/f$. For the second type a minor deviation from $1/f$ - dependence can be due to RTS often present in nanotube FETs (Liu et al., 2006b; 2006c; 2008). It is generated by the trapping-detrapping of carriers by tunneling into traps in the SiO_2. Therefore the RTS provides a way to probe the tunneling density of states of the CNT itself. Observed deviation can be well explained by the addition of a generation-recombination noise term which adequately describes RTS,

$$S_I = \frac{AI^2}{f} + \frac{BI^2}{1+(f/f_0)^2} \, ,$$ (11)

where f_0 is the characteristic frequency for the G-R noise. For the case of mobility fluctuations, Hooge's empirical rule (see Eq. (5)) states that the noise coefficient A is given by Eq. (6). Since the total number of carriers in the system $N = C_g L |V_g - V_{th}|/e$ in a one dimensional FET in the on state, the abovementioned equation may be rewritten as

$$\frac{1}{A} = \frac{C_g L |V_g - V_{th}|}{e \alpha_H} \, ,$$ (12)

where C_g is the gate capacitance per length (Yao et al., 2002), V_d, V_g and V_{th} are the drain voltage, gate voltage, and device threshold voltage, respectively. The amplitude of $1/f$ - noise is inversely proportional to $|V_g - V_{th}|$ indicating mobility fluctuations and ruling out number fluctuations as the cause.

The carrier traps in the oxide (Javey et al., 2003) change the effective gate potential by modifying the threshold voltage of the transistor. Effect of single trapped charges in a CNT-FET is determined: a single charge can shift and even rescale the entire transfer characteristic of the device (Kim et al., 2008). This can explain both the large RTS noise and the large variations between nominally identical devices. It is examined the dependence on both the thickness and dielectric constant of the gate dielectric, suggesting routes to reduce electrical noise. A correlated RTS is observed from the interaction of two individual defects in a CNT transistor (Wang et al., 2007). It is shown that the amplitude fluctuation of one defect significantly depends on the state of the other defect.

For the back gated CNT-FET, it is shown that source-drain current at fixed gate potential can drift in time due to significant nanotube-substrate interactions (Fuhrer et al., 2002; Radosalvljevic et al., 2002). Such drift can introduce LF noise components greater than those from the CNTs themselves. In (Liu et al., 2006a; 2006b; 2008) a correlated RTS is observed from the interaction of two individual defects in a CNT. It is shown that the amplitude fluctuation of one defect significantly depends on the state of the other defect. Moreover, statistics of the correlated switchings is shown to deviate from the ideal Poisson process. Physics of this RTS correlation is attributed to the fact that the two defects are located closer than the sum of their Fermi-Thomas screening lengths. The switching of resistance between two discrete values, known as RTS noise, was observed in individual carbon SWNT (Jhang et al., 2005). The RTS noise has been studied as a function of bias-voltage and gate-voltage as well as temperature. By analyzing the features of the RTS noise, authors identify three different types of RTS noise existing in the SWNT

related systems. While the RTS noise can be generated by the various charge traps in the vicinity of the SWNTs, the RTS noise for metallic SWNTs is mainly due to reversible defect motions between two metastable states, activated by inelastic scattering with electrons. It is shown that the 1/f-noise in single CNT-FETs is strongly dependent on temperature between 1.2 and 300 K (Tobias et al., 2008).

The physical mechanism of the RTSs observed in the single-walled CNT-FETs was explained to be due to the hopping/tunneling of carriers between the conducting channels of the SWNTs and the defect levels (Liu et al., 2006b). The defects were hole-type Coulomb repulsive centers located near the valance band of the SWNTs in the energy space and at the interface and/or several nanometers underneath SWNT in the real space. The contribution of the current fluctuations is mainly due to mobility modulation, and the large amplitude of the RTSs is analyzed to be due to the small diameters of the SWNTs. The only known way to reduce $1/f^{\gamma}$ -noise is achieved by using a free standing CNT as an island (Roschier et al., 2001).

Tobias and coauthors used Hooge's relation simply as an empirical rule for characterizing the magnitude of the noise by a single (temperature dependent) parameter $\alpha(T)$ (Tobias et al., 2008). Experiments showed that $\alpha(T = 300K)$ is the same for CNTs from 1 to 30 μm long, and indicate that the fluctuating resistance responsible for the 1/f-noise is indeed from the length-dependent diffusive resistance of the CNT channel, not the contact resistance. Investigated samples are made using chemical vapor deposition grown CNTs, and contain single CNTs contacted by Pd/Nb leads. The devices were above a layer of 400 nm of thermally grown SiO$_2$ with a heavily doped Si substrate to allow for back gating of the devices down to cryogenic temperatures. Here were presented data from two devices taken in a gas flow helium cryostat, with temperatures ranging from 1.2 to 300 K. Device 1 has a diameter 1.4 nm, and device 2 has a diameter of 1.9 nm. The devices each have a length of 3 μm. The number of carriers is determined by assuming that the device is in the linear regime. This gives the number of carriers to be linearly proportional to the gate voltage: $N = C_g \left| V_g - V_{th} \right| / e$, where C_g is the capacitance of the CNT to the gate electrode, V_g is the gate voltage, V_{th} is the threshold voltage. The gate capacitance is determined by modeling the CNT as a wire over a two dimensional plane: $C_g = 2\pi\varepsilon\varepsilon_0 L / \ln(4h/d)$, where ε_0 is the dielectric constant, $\varepsilon = 2.45$ is the average of the dielectric constants of vacuum and SiO$_2$, h is the dielectric thickness, L is the length of the tube, and d is the CNT diameter. Spectrum of noise from a CNT-FET at a bias voltage shown on linear-linear scale (main panel) and log-log scale (inset) shown in the Fig. 5. The value of the Hooge parameter $\alpha(T)$ can then be determined from the slope of the $\langle 1/A \rangle$ versus V_g plot, which is equal to $C_g / e\alpha(T)$. Note that extraction of $\alpha(T)$ in is insensitive to changes in carrier number caused by, e.g., changes in the threshold voltage with temperature. Authors discussed the peak in $D(E)$ at $E \sim 0.4$ eV and argue that this feature, i.e., the broad peak that ranges from -0.2 to 0.6 eV, is responsible for the majority of the room temperature noise. The low-energy behavior of $D(E) \sim 1/E$ corresponds to an approximately temperature independent Hooge parameter. Thus, the rise of the Hooge parameter by a factor of ~20 from low temperature to room temperature is due entirely to the broad peak in $D(E)$ around 0.4 eV. The characteristic energy scale allows to rule out some possibilities for the source of the noise. The energy scale is comparable to the band gap (~0.5 and ~0.37 eV for devices 1 and 2, respectively)

and, therefore, one can rule out electronic excitations (e.g., defect ionization, etc.) within the CNT itself as the major noise source; such mechanisms should have characteristic energies less than or equal to half the band gap. Temperature dependence of the Hooge parameter for both CNT devices was presented in Fig. 6.
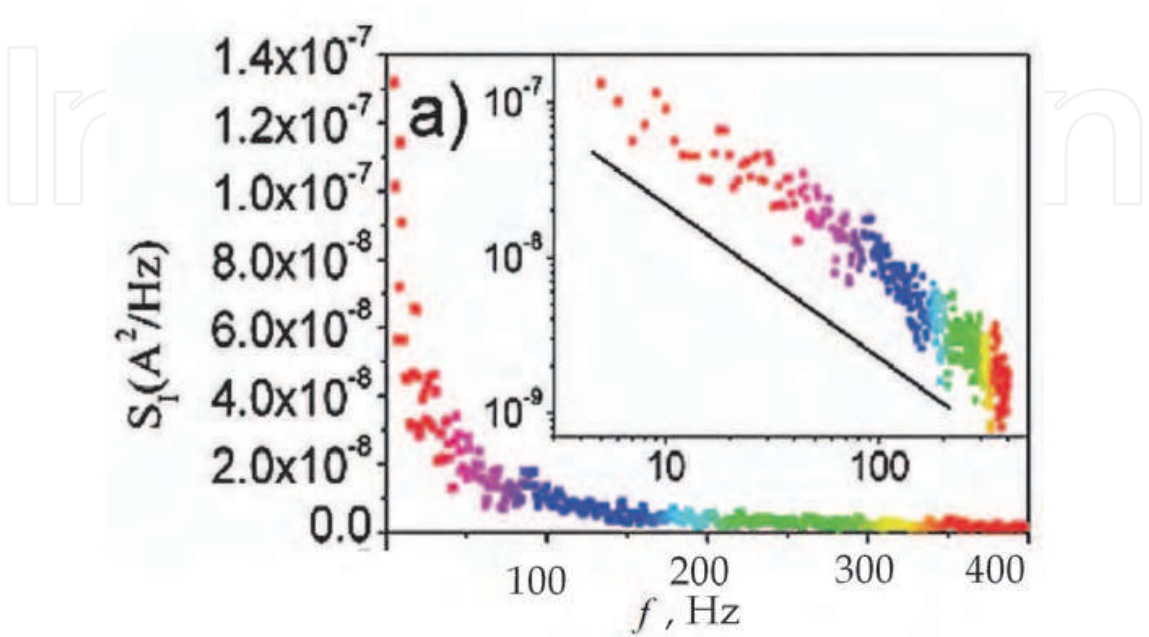

Fig. 5. Spectrum of 1/f -noise for a CNT FET at a bias voltage of 100 mV with each frequency point color coded a gate voltage of −8V, and a T=150 K, shown on linear-linear scale (main panel) and log-log scale (inset). The solid line in the inset indicates a slope of −1 (Tobias et al., 2008).
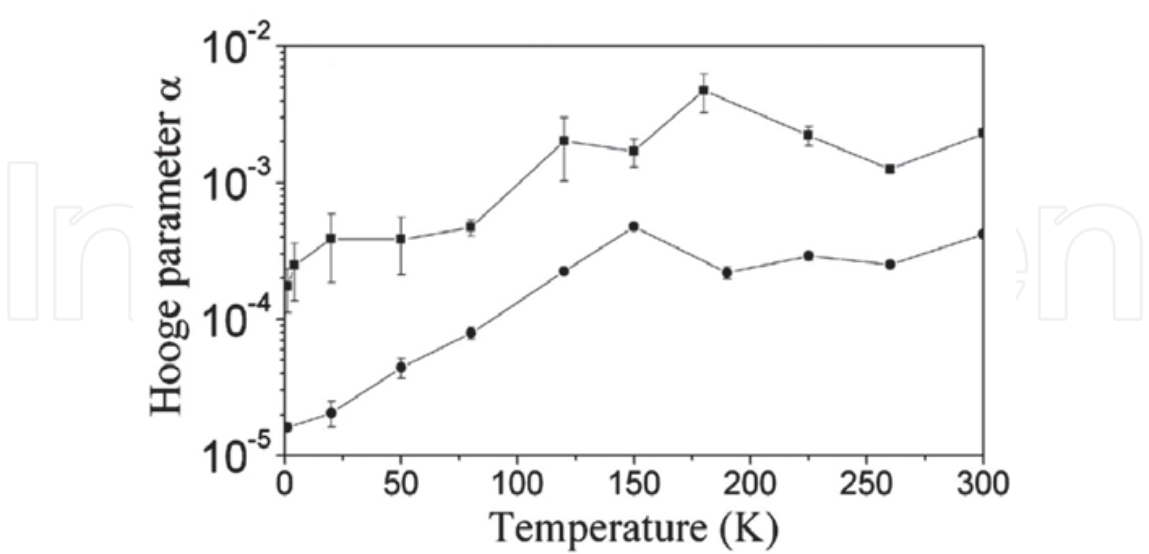

Fig. 6. (a) $\alpha(T)$ dependence for both CNT devices. The data points are calculated using data shown in Fig. 5. The significant upward trend between 1.2 K and about 150 K is seen in both samples. Filled squares and circles correspond to device 1 and device 2, respectively (Tobias et al., 2008).

Authors used the model of Dutta & Horn (Dutta & Horn, 1981) to extract the distribution of activation energies of the fluctuators $D(E)$, which shows two features: a rise at low energy with no characteristic energy scale, and a peak at energy of order 0.4 eV. The magnitude of the peak energy rules out physisorbed gas molecules with low binding energy, and electronic excitations or structural fluctuations of the CNT itself, as sources of room temperature noise. The gate voltage dependence of the noise additionally rules out potential fluctuations resulting from charge trapping and detrapping in the gate dielectric. The likely sources of the noise are the motion of defects in the gate dielectric or at the CNT-dielectric interface, or possibly strongly physisorbed (binding energy ~0.4 eV) species on the CNT or dielectric surface. The dependence of the noise on the reciprocal of the number of carriers in the sample is taken as evidence that the $1/f$ -noise originates in the bulk rather than on the surface; since N scales with volume Ω, the noise power $S_I \propto 1/\Omega$. However in a 1D system such as CNTs, N is proportional to the length of the system; no useful distinction can be made between the surface area and the volume, hence no distinction between surface and bulk origins of the noise can be made from the N dependence.

The $1/f$ -noise amplitude is reduced by about one order of magnitude when the NT is suspended, suggesting that the $1/f$- noise is dominated by the trapped charges in the oxide (Lin et al., 2007a). The authors study the electrical noise of CNT lying on the substrate and when being suspended by measuring the current fluctuations at a DC bias. In CNT devices, the LF current fluctuation is dominated by the $1/f$-noise, which is proportional to the square of the DC current and can be expressed by Eq. (5), with $\beta = 2$ and $\gamma = 1$. Before the etching, the current power spectra of these devices all exhibit the f^{-1} dependence with similar A values of 6×10^{-5}, 6×10^{-5}, and 8×10^{-5} for devices 1, 2, and 3, respectively. After the etching, the suspended CNT devices, 1 and 3, both show a significantly reduced $1/f$ -noise level with A of 1.2×10^{-5} and 1×10^{-5}, respectively. In contrast, the device 2 possesses the same $1/f$ -noise level after the process.

These results unambiguously confirm that the oxide substrate is one of sources of $1/f$ -noise in SWNT devices and provides insight into schemes to reduce the $1/f$ -noise in CNT devices.

3.3 Different CNT surroundings and the noise fluctuations in the channel

LF noise amplitude and frequency behavior are very sensitive to surrounding environment and to devices work conditions. It is found that the signal-to-noise ratio (SNR) is gate-potential dependent for liquid-gated SWNT transistors. The SNR is lowest in the ON-state where additional contributions to the noise lead to a decrease in the SNR by up to a factor of 5 for bare devices (Heller et al., 2009).

LF noise measurements have been performed on a single-walled CNT connected by Ti/Au electrodes. It has been found that the $1/f$ -noise decreases when the measurements are undertaken under vacuum and when the CNT is partially degassed, showing a correlation between the fluctuation inducing the $1/f$ -noise and the presence of gases (Soliveres et al., 2006). It was shown that the $1/f$ -noise sources are located at the metal/NT contacts and that parameter A appears to be proportional to the sample resistance by a proportionality factor close 10-11 Ohm-1. Authors note that result $A = 1.0 \times 10^{-11} R$ may seem surprising as the transport is ballistic in individual CNTs and diffusive in films or mats. It was also shown that when the device is under vacuum, the effects of gases are reduced and A decreases.

Ambient gases can be considered to be at the origin of the fluctuations leading to the $1/f$ - noise. Excess noise with a slope different from unity can be explained by a superposition of a few Lorentzians and of the $1/f$ -noise. The change in slope with respect to temperature is thus explained by the variation of trap activities. Lorentzians are associated to defects or strongly bounded molecules remaining on the CNT surface. Results (Postma et al., 2001; Tarkiainen et al., 2005) have shown A to be dependent on resistance of individual CNTs. In particular, the $1/f$-noise level of CNTs was found to barely vary, within a factor of two, in different gas environments at room temperature (Kingrey et al., 2006).

LF-noise measurements on individual single-walled CNT transistors exhibiting ambipolar characteristics with a polymer electrolyte as gate medium have been performed. LF-noise can be monitored in both p- and n-channel operation of the same CNT under the same chemical environment. $1/f$ -noise in the p-channel of polymer electrolyte gated CNT transistor is similar to that of back gate operation. However, most devices exhibit significantly larger noise amplitude in the n-channel operation that has a distinct dependence on the threshold voltage. A nonuniform energy distribution of carrier trapping/scattering sites is considered to explain these observations (Back et al., 2008).

As reported in the literature (Liu et al., 2006a; Collins et al., 2000; Lin et al., 2006), unpassivated CNT transistors show high amplitudes of LF-noise. This is mainly due to the fact that the CNT is exposed to various environmental factors, such as water molecule (Bradley et al.; 2003), mobile ions (Fuhrer et al., 2002). Chan with co-workers (Chan et al., 2010) studied the effect of electron beam exposure on CNT-FETs. The authors found that trapped charges induce the barrier along the channel, and transport is dominated by the tunneling events across this barrier. Results of noise measurements demonstrate a transition from $1/f$ -noise described by $S_I = AI^2/f$ to shot noise with $S_I = 2eI$ noise behavior with one order of magnitude increased noise amplitude above 1 kHz frequency. These noise investigations allow also following transport transformation from dominated by normal diffusive processes to transport dominated by tunneling events, respectively.

The $1/f$ -noise in individual semiconducting CNT in a FET configuration has been measured also in ultrahigh vacuum and following exposure to air (Ishigami et al., 2006). In this case the amplitude of the normalized current NSD is independent of source-drain current and inversely proportional to gate voltage, to channel length, and therefore to carrier number, indicating that the noise is due to mobility rather than number fluctuations. Hooge's constant for is found to be $(9.3 \pm 0.4) \times 10^{-3}$. The magnitude of the $1/f$ -noise is substantially decreased by exposing the devices to air. The gate-voltage and channel-length dependence of the amplitude of the $1/f$ -noise is consistent with Hooge's empirical rule for noise caused by mobility fluctuations and not by number fluctuations (Ishigami et al., 2006). It was found that the $1/f$ -noise decreases when the same devices are subsequently measured in air. In the linear I-V regime, $1/f$ -noise changed according Eq. (5), with $\beta = 2$ and $\gamma = 1$. In experiment is typically found $S_I \propto I^{2 \pm 0.1}$.

Unique transport dynamics has been registered in current noise of CNT-FETs fabricated on B-doped Si substrate (Chan et al., 2009). It is shown that different molecules create different, resolvable traps that are detectable in the current noise. Therefore "receptor" states may be engineered along a nanotube that electrostatically couple to noncovalently bound targets for detection with ultrahigh specificity.

In (Mannik et al., 2008) was collected a reliable set of experimental data to analyse the mechanism responsible for the LF noise in liquid-gated SWNT-FETs and its scaling with the length of the nanotube channel down to nanometer scale. SWNTs were grown by CVD onto Si wavers with a 500 nm thick SiO$_2$ layer. SWNT diameters were 2.0 nm and contacted with Au top electrodes with a 2.0 nm underlayer of Cr. Channel length was below 100 nm. Authors registered that the ionic strength of the surrounding electrolyte has a minimal effect on the noise magnitude in SWNT-FETs. The results show that the gate dependence of the noise amplitude provides strong evidence for proposed charge-noise model (Tersoff, 2007). Charge noise dominates the noise of SWNT-FETs in the subthreshold region, commonly used for sensor applications. It is emphasized two properties of N that hold irrespective of the ballistic or diffusive nature of electronic transport in SWNTs:

i. N, and thus $S_I(1\text{Hz})/I^2$, as a function of liquid-gate voltage follows an exponential law in the subthreshold region with the same exponential slope as the source-drain current (Tersoff, 2007), and

ii. N scales with the channel length as $N \propto L$ at fixed gate voltage.

Comparison shows that the Hooge model fails to describe the experimental data. It is noted that all devices yield remarkably comparable A values that are quite independent of the channel length, except for the shortest device in the subthreshold region. It is concluded also that the charge-noise model presents an accurate description of experimental data in the threshold regime of SWNT-FETs. The level of charge-noise is higher for SWNT-FETs with short CNT lengths. It appears that

$$S_I(1\text{Hz}) \propto S_{input}\left(\frac{dI_{sd}}{dV_{lg}}\right)^2 ,$$ (13)

and $S_{input} \propto 1/L$. Here V_{lg} is the electrolyte potential. This dependence explained as follows. In the charge-noise model the voltage fluctuations of the gate, described to be proportional to constant S_{input}, are the result of charge fluctuations, S_q. These fluctuations couple to the SWNT-FET through some effective gate capacitance, C_{gate} so that

$$S_{input} = \left(\frac{dV_{lg}}{dq}\right)^2 S_q = \left(\frac{1}{C_{gate}}\right)^2 S_q .$$ (14)

The effective gate capacitance scales as $C_{gate} \propto L$ and is presumably dominated by the quantum capacitance (Rossenblatt et al., 2002). In the other hand, a homogeneous distribution of independent charge fluctuations along the length of the SWNT leads to $S_q \propto L$. Combining these dependencies for C_{gate} and S_q gives $S_{input} \propto 1/L$. This dependence also excludes that charge fluctuations in the SWNT-metal contacts are the dominating source of noise. Tersoff has proposed to include an extra term in the noise expression similar to the Hooge model

$$S_I = S_{input}\left(\frac{dI}{dV_{lg}}\right)^2 + AI^2 .$$ (15)

Moreover, it has been shown that for a single-protein adsorption event the SNR is proportional to $\frac{1}{C_g}\frac{dI}{dV_{lg}}\frac{1}{\sqrt{S_I}}$, which scales as $L^{-1/2}$. Therefore, the shortest channel length should be used to detect the single molecule event. However, for the case of increased sensitivity to the lowest analyte concentrations, a longer channel length should be used, taking into account that the total number of analyte molecules on the CNT is proportional to the length. In the latter case, the SNR is scaled with the length as $L^{1/2}$.

Thus a CNT as a one-atom-thick crystal layer is strongly sensitive to the surface conditions, therefore transport phenomena and noise properties of CNTs can be used for the development of chemo- and biosensors and indentification of individual molecules.

4. Noise peculiarities in carbon nanotube thin films

4.1 Advantages and disadvantages of CNT networks

The CNT networks may maintain the unusual electronic and sensors properties of individual SWNTs. They allow constructing devices of arbitrary size using conventional microfabrication technologies and improved impedance matching that is especially important for high-frequency device applications. The intertubes barriers and defects, length of the individual CNTs in the assemblies as well as contact geometry play an essential role in the electrical transport properties of the CNT arrays. Therefore different charge transport mechanisms can be observed in the arrays of CNTs: metallic conductivity, variable range hopping (VRH), weak localization (WL), and fluctuation induced tunneling. Combination of various mechanisms is possible as well. Electronic and transport properties of CNTs and mechanisms responsible for the charge transport in CNTs assemblies detailed presented by Charlier and Ksenevich with co-authors (Charlier et al., 2007; Ksenevich et al., 2010). Current noise can be used to study cross-correlation processes in carbon nanotubes networks to detect statistical correlations in quantum transport. Noise is more sensitive to percolation transport in networks than resistivity and provides important fundamental insights into physics of percolation transport in CNTs networks and films. At the same time tube-tube junctions in the networks may result in increasing flicker noise level, as will be shown below in section 4.3.

Transformation of 1/f -noise behavior from the case of single CNT to the case of crossing CNTs was studied by Collins for the SWNT (Collins et al.,2000) and Quacha for the MWNT (Quacha et al., 2002). The room temperature noise characteristics of SWNTs in different configurations, ranging from isolated individual tubes to 2D "films" and 3D "mats" of randomly interconnected CNT assemblies were studied in (Collins et al., 2000). It is finding that all SWNT samples, irrespective of the contact electrode or tube connectivity configuration, display similar excessive 1/f -noise which cannot be explained within the idealized context of covalently bonded metallic wires. Fig. 7 depicts the noise power at different bias currents measured across an isolated, single SWNT. At zero bias current, the noise was flat and agreed with the thermal Nyquist level $S_V = 4kTR$ (dashed line). At finite bias currents excess noise is observed. After subtracting the thermal baseline, the excess noise varies as $1/f^{\gamma}$, with $\gamma = 1.06 \pm 0.02$ for all bias currents within the linear-response regime. A bias current dependence of the form I^{β} is found, with $\beta = 1.99 \pm 0.4$. To characterize the absolute amplitude of the excess noise the voltage (current) noise power S_V (S_I) expressed as Eq. (5) and:

$$S_V = A \frac{V^2}{f^\gamma},$$ (16)

where $A = 1.0 \times 10^{-11} R$ at $\gamma = 1.06$, R is the resistance.

Estimating for the SWNT of Fig. 7 $N \sim 10^4$ atom using Eq.(6) gives $\alpha_H = 0.2$ for SWNTs, in sharp disagreement with Hooge's law. In semiconductors and very small metal whiskers, where surface and impurity fluctuations can dominate typical bulk effects, α_H may be substantially larger than 0.002. The large value of α_H observed in the first experimental studies for SWNT similarly suggests that surface fluctuations play an important role, a result not totally unexpected if one considers that every atom that constitutes a SWNT is a surface atom. Parameter A scales with R can also be illuminated by Hooge's law. Combining $A = 10^{-11} R$ with Hooge's law gives $A = \alpha_H / N = 10^{-11} R$, whereby the number of carriers N is simply proportional to the sample conductance $G = R^{-1}$. From a qualitative point of view, this relationship merely reflects that both N and G depend on the number of parallel, conducting SWNTs in the sample.

A linear increase of noise level with resistance can be understood if the samples consist of several parallel conduction channels. In this case the resistance is inversely proportional to the number of channels M, while $1/f$-noise spectral density, according to Hooge's empirical formula scales as $\propto 1/N$, where number of free charge carriers proportional to system size (Hooge, 1969, 1994; Hooge et al., 1981). As $N \propto M$, it follows that $S_I \propto R$. This reasoning applies to a selection of samples, in which the conductivity is determined by the number of parallel conduction paths. On the contrary one would expect the resistance to be directly proportional to sample length L, as well as $N \propto L$, which would give $S_I \propto 1/R$. Such dependence is not observed.
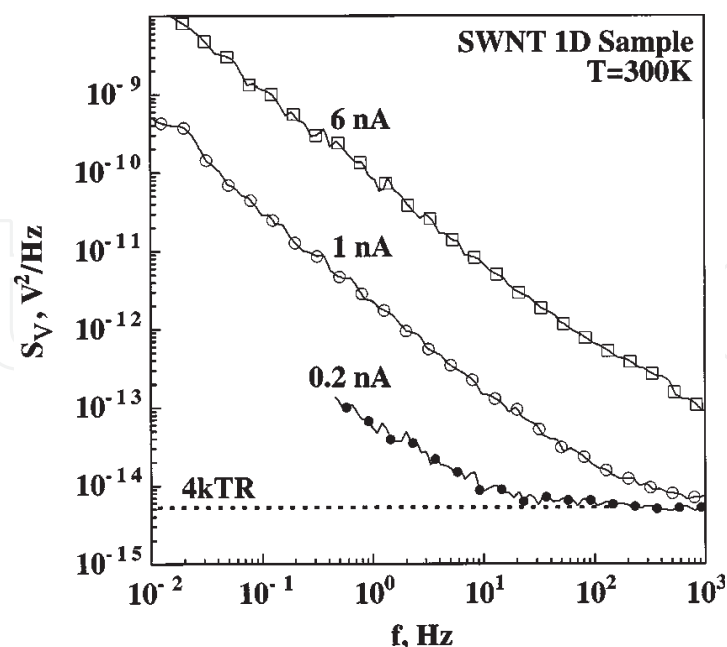

Fig. 7. $S_V(f)$ dependence for a single SWNT, for three values of applied bias current. The SWNT has a two probe resistance of 335 kΩ (Collins et al., 2000).

Carbon composite resistors considered unsuitable for most low-noise circuitry, have excess noise amplitudes between 10^{-15} and 10^{-13} (for $R \leq 1k\Omega$). Carbon fibers with resistances $\leq 1k\Omega$ show similar noise magnitudes. Hence, 1/f-noise in SWNT conductors is four to ten orders of magnitude larger than that observed in more conventional conductors. Very low 1/f -noise, $A \approx 10^{-13}$ was recorded for a thick rope of SWNTs (Roche et al., 2002).

For low crossing MWNT $S_V \propto V^{1.56}$ (Ouacha et al., 2002). Note, that for an individual MWNT $S_V \propto V^{1.02}$. Fig. 8 shows the voltage noise density as a function of frequency, at a bias voltage of $V = 0.1$ V for 1MWNT and 2MWNT. It is found $\beta = 1.98$ for 1MW and 2.63 for 2MWNT. For 1MW, γ ranges between 0.96 and 1.14 with an average value of 1.04, this implies that the excess noise found in 1MW is consistently 1/f -like. Similar values, i.e., γ close to unity was found for iron-filled MWNTs (Roumiantsev et al., 2001). Actually, this type of noise is found in a wide variety of systems (Hooge, 1969) and the form expressed by Eq. (5) and Eq. (16) indicates that the origin of the measured noise is conductance fluctuations. However, for the 2MWNT sample a different behavior is observed, i.e., γ is found between 1.49 and 1.63, with an average value of 1.56. A value of 1.5 for γ suggests a diffusion process between two different media. The sample 2MWNT consists of two crossing multiwalled CNTs, hence a CNT–CNT junction is formed. According to authors diffusion of carriers between the CNTs occurs and is responsible for the noise observed in 2MWNT. However, other mechanisms may also contribute to the 2MWNT noise, such as the forces between the two crossing CNTs which have consequences on the geometric structure of the CNTs. It is found that the noise in 2MWNT at higher frequencies is very close to the shot noise, which suggests the presence of an electrical barrier at the CNT–CNT junction (Ouacha et al., 2002).
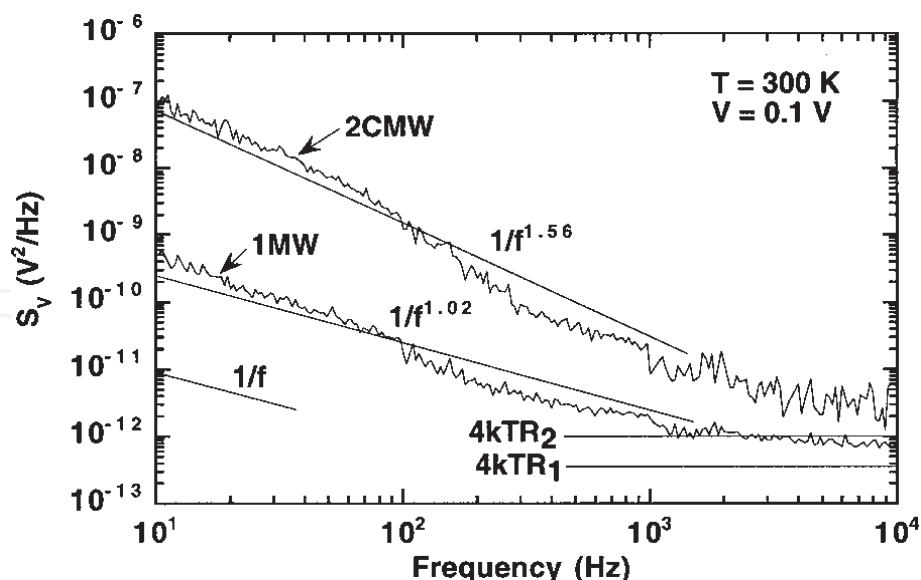

Fig. 8. Voltage noise power S_V as a function of frequency (Ouacha et al., 2002).

Peculiarities of noise have been registered in ultralow-power alcohol vapor sensors using MWCNTs (Sin et al, 2007). Unlike other types of noise, such as thermal noise or shot noise, which are not material-specific properties, parameter A in Eq. (16) generally reflects the sample quality and, most importantly, increases with decreasing device size.

For metallic CNTs, the noise amplitude A is roughly proportional to the device resistance R (Collins et al., 2000). In semiconducting CNTs, A is further modulated by the gate voltage that varies the device resistance, showing an experimental dependence $A \propto 1/N$, where N is the number of atoms or carriers in the system. High quality metal films tend to have values of A as small as 10^{-19}, with values increasing to 10^{-17} for thin films with strong grain boundary effects. At a very large current, $I = 0.1$ mA, $A \approx 10^{-10}$ has been observed for a MWNT, but that value is not likely to extrapolate well down to low currents (Vajtai et al., 2002).

Recently, another interesting effect have been demonstrated in CNT network using noise spectroscopy. Thin film network of CNT-FETs allows novel functionality – fluctuation enhanced sensing (FES) for detection of N_2O, CO, H_2S and H_2O vapor have been demonstrated (Haspel et al., 2008). The FES method is capable of increasing the chemical selectivity of carbon nanotube sensor, when using the amplitudes of the acquired power spectral density as sensor signal. Electrical noise can also help pulse-train signal detection at the nanolevel for various types of threshold units represented by carbon nanotubes (Lee et al., 2006). Small amount of noise allows enhancing the nanotube detector's performance on subthreshould level using stochastic resonance effect. Such noise-enhanced signal processing at the nanolevel promises applications to signal detection in wideband communication systems, biological and artificial neural networks.

4.2 Tube-tube junction noise and collective phenomena

Large noise coefficients obtained for CNT-FETs suggested that CNT–CNT junctions, not the CNTs themselves, are the dominant source of $1/f$-noise in the composite paper (Imam et al., 2010; Tanaka et al., 2010). Electrical transport and noise in semiconducting CNTs is investigated in (Raychaudhuri, 2002). By studying CNT devices with various diameters and contact metals, it is show that the ON-currents of CNFETs are governed by the heights of the Schottky barriers at the metal/CNT interfaces. The current fluctuations are dominated by $1/f$-noise at LF and correlate with the number of transport carriers in the device regardless of contact metal. The noise characteristics of randomly networked single-walled CNTs are studied with FETs in (Tersoff, 2007). Fluctuation-induced tunneling conductivity model was proposed for disordered heterogeneous systems on the contrary to the systems with hopping charge carrier transport between localized sites. Different types of CNTs arrays with existing electrical barriers can be also considered as heterogeneously disordered systems. Therefore this model was used for describing the temperature dependence of conductivity of single-walled CNTs fibers and networks. Sangwan with co-authors demonstrated that suspended carbon nanotube network shows ambipolar transport behavior with negligible hysteresis (Sangwan et al., 2008). The Hooge's constant of the suspended CNT-FETs is about 20 times lower (2.5×10^{-3}) than for control CNT-FETs on SiO_2.

Beyond the fundamental interest in understanding the transport properties of 1D system, the integration of CNTs in electronic devices such as FETs raise the question of the contact resistance, that is, the ability for electrons to jump from a metallic electrode, used as the source or drain, onto the CNT. In particular, in contrast to the predictions of quantized conductance obtained for clean infinite systems, for a CNT/electrode contact a lowering of the transmission across the interface systematically obtained. As first analyzed by Chico and co-workers (Chico, et al., 1996), even for the most favorable case, i.e., for an intramolecular CNT based heterojunction, the symmetry mismatch between incoming and outgoing

electronic states yields a transmission probability lower than 1. Intramolecular junctions have been experimentally observed by scanning tunneling microscope (Odom et al., 2002). The reduction of transmission at the interface is general to all realistic nanoscale junctions between a CNT and a metallic electrode, or other interface geometries leading to different charge injection capabilities.

Detailed analysis is performed with the parameters of number of mobile carriers and mobility in the different environment. This shows that the change in the number of mobile carriers resulting in the mobility change due to adsorption and desorption of gas molecules (mostly oxygen molecules) to the tube surface is a key factor in the $1/f$ -noise level for CNT network transistors (Kim et al., 2008). In order to avoid additional LF noise contribution from SiO_2-CNT interactions, the measurements were carried out in conducting liquid and $1/f$ -noise in CNT-FETs as a function of gate potential (Briman et al., 2006). The measured LF-noise for CNT/cellulose composite paper exhibited $1/f$-characteristics and can be explained by Hooge's empirical law (5). The reduction in the intertube electrical transport barrier and decreasing of noise was found after thermal annealing of SWNT films (Lu et al., 2008). The noise spectra can be described by $S_V = A V^2 / f$ with A decreased by 80% after annealing to value of 5.64x10^{-12}.

Kim and co-authors in 2007 studied noise properties in ballistic SWNT and obtained power law dependence at low bias voltages. The measurements demonstrate that noise studies are powerful method for collective phenomena study for the case of a Tomonage-Luttinger Liquid interaction effects in the SWNT devices.

4.3 Noise as sensitive tool for percolation

From a microscopic point of view, two charge transport mechanisms occur in the films: the transport along CNT themselves and the transport between crossed CNTs. Considering the large mean free path in CNTs and the weak coupling between CNTs, Soliveres and co-authors assume that the contacts between CNTs dominate the transport through the film (Soliveres et al., 2009). From a macroscopic point of view, the CNT film is modeled as a percolation network. Percolation networks have electrical properties that vary rapidly at the vicinity of the percolation threshold and follow power laws related to the density of CNTs. The conductivity and noise coefficient A were measured for the different densities. These two quantities follow power laws with critical exponent t_c for the conductivity and k for the noise, as expected in percolation processes.

$$A \propto \left(\frac{RS}{L} \right)^w ,$$ (17)

where $w = k/t_c$, R is the film resistance, S is the section area.

Based on the experimental results in (Briman, et al., 2006) it is concluded that the number of carrier fluctuations is the source of the $1/f$ -noise. In (Akabane & Miwa, 2009) the resistance fluctuation of CNTs in vacuum low temperature with laser irradiation is measured and the origin of mobility fluctuation is suggested.

Behavior of the $1/f$ -noise scaling is observed in percolating systems (Snow et al., 2004). In 2D-network devices consisting a large number of intersecting SWNTs confirmed the V^2/f scaling

of the LF noise. This behavior contrasts the scaling observed between two crossed MWNTs that deviate significantly from the V^2/f behavior (Ouacha et al., 2002). Using the $f = 10$ Hz noise it is plotted the scaled noise, $A = fS_V/V^2$ versus device resistance (Fig. 9). The solid line in the Fig. 9 is a plot of $A = 10^{-11}R$. Note that the level of noise in these devices and the noise levels observed in (Collins et al., 2000) are in good agreement. The measured data indicate that the resistance value alone is insufficient to predict the level of 1/f-noise. Note that the 1/f - noise magnitude in devices discussed in (Snow et al., 2004) also does not correlate well with the resistance. So, the device size is an important additional component in predicting the magnitude of 1/f-noise. In order to observe this size dependence in (Snow et al., 2004) plot this same data set as A/R versus the electrode spacing L (see Fig. 10).
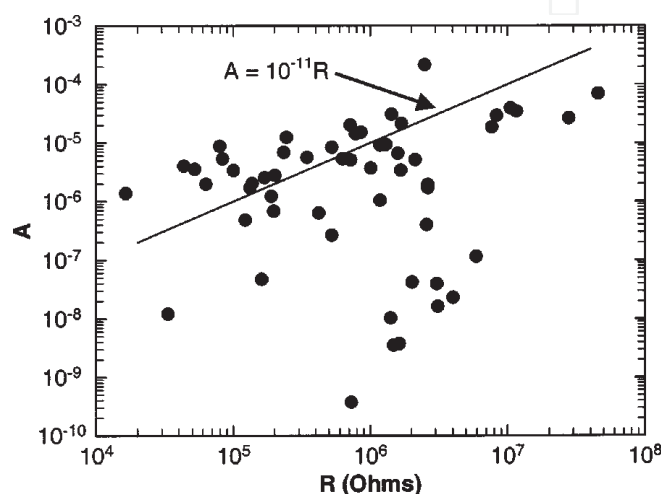

Fig. 9. Plot of the scaled noise, $A = fS_V/V^2$, measured in 2D networks versus the device resistance. The solid line corresponds to the empirical relationship established in (Collins et al., 2000) (Snow et al., 2004).
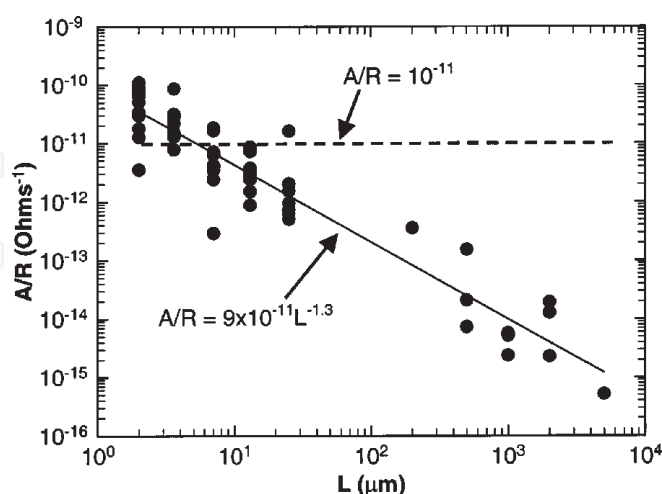

Fig. 10. The same data as in Fig. 9 plotted as A/R versus the electrode spacing L. The dashed line represents $A/R = 10^{-11}$ (Collins et al., 2000) and the solid line is a least-squares power-law fit to the data. A clear relationship between the level of 1/f -noise and the device size is established (Snow et al., 2004).

Power-law fit of the data (solid line) yields:

$$A/R = 9 \times 10^{-11}/L^{1.3} \, , \tag{18}$$

where L is in units of mm. The resulting empirical formula

$$S_V = 9 \times 10^{-11} \frac{R}{L^{1.3}} \frac{V^2}{f} \tag{19}$$

is a good predictor of the LF noise in SWNT networks ranging in resistance from $10^4 \div 10^7 \, \Omega$ and spanning device areas from 10 to 108 μm². It is shown that for films, A is inversely proportional to the dimensions of the bulk but remains proportional to $10^{-11} \, \Omega^{-1}$ (Snow et al., 2004).

For comparison, this expression predicts that a 1-mm-sized, 1 MΩ SWNT sensor biased at 10 nA will exhibit 1/f-noise in excess of the background thermal noise $(S_V = 4kTR)$ for $f < 70$ Hz. The reduction of the 1/f-noise with device size is consistent with other electronic systems in which the magnitude of the 1/f-noise varies inversely with the number of charge carriers N in the device. According to this behavior the 1/f-noise should scale as R/L^2 (i.e., $R/L^2 = 1/e\mu N$). The R/L^2 behavior assumes a uniform system of uncorrelated noise sources that number in proportion to N.

In contrast, the SWNT network consists of many parallel one dimensional paths formed by intersecting SWNTs. The SWNTs consist of a mixture of both metallic and semiconducting CNTs that have large variations in resistance, which results in nonuniform voltage drops along the conduction paths. Thus, the dominant noise sources will occur at the high-resistance segments of the current paths. The gate field might also produce charge fluctuations in the SiO₂ gate dielectric that increases the level of 1/f-noise. In Fig. 11 presented the normalized resistivity fluctuations $S_\rho/\rho^2 \left(=S_V/V^2\right)$ versus resistivity ρ.

On the basis of the statistics of a large number of devices consisting of mixtures of different types of CNTs (i.e., 2D mats and 3D networks), it has been concluded that the 1/f-noise amplitude in these CNT-based devices increases with the sample resistance R with an A/R ratio depending on device dimensions (Snow et al., 2004).

The results of Monte-Carlo LF noise simulations as a function of film thickness, width and length were presented and compared with experimental data (Behnam et al., 2008; 2009). By comparing the simulation results with the experimental data, it is finding that the noise generated by tube-tube junctions dominates the total CNT film 1/f-noise. It is also show that the 1/f-noise amplitude depends strongly on device dimensions, CNT degree of alignment, and the film resistivity, following a power-law relationship with resistivity near the percolation threshold after properly removing the effect of device dimensions. It is find that the critical exponents associated with the noise-resistivity and noise-device dimension relationships are not universal invariants, but rather depend on the specific parameter that causes the change in the resistivity and 1/f-noise, and the values of the device other parameters. Since 1/f-noise is a more sensitive measure of percolation than resistivity, these simulations not only provide important fundamental physical insights into the complex interdependencies associated with percolation transport in CNT networks and films, but also help understand and improve the performance of these nanomaterials in potential device applications, where noise is an important figure of merit.
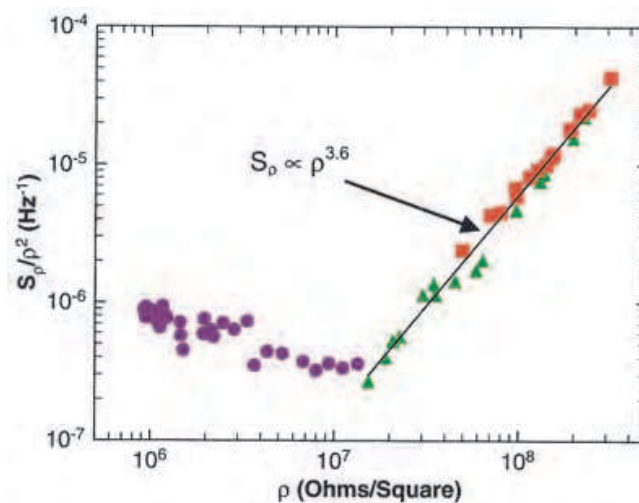
Fig. 11. S_ρ / ρ^2 vs ρ. The circles correspond to $V_g < 0$ V, the triangles to $0 < V_g < 1.6$ V, and the squares to $V_g > 1.6$ V. As the gate bias shuts off the current in the network, the noise increases as a power law of the resistance. This behavior is similar to the 1/f -noise scaling observed in percolating systems (Snow et al., 2004).

To model physical properties of the film, the resistance of an individual CNT is calculated by the expression $R_{CNT} = R_0 L / \lambda$. For computing the 1/f -noise in the CNT film it is used a model which takes into account the noise contributions from both the CNTs themselves and the tube-tube junctions in the film and assumed $\lambda \approx 1$ μm. Assuming independent noise sources the relative 1/f-noise magnitude of the film, A_{eq}, can be written as

$$A_{eq} = \frac{S_I f}{I^2} = \frac{1}{V^2 I^2} \sum_n i_n^4 r_n^2 A_n \,,$$

where i_n is the current, A_n is the relative 1/f -current noise amplitude, and r_n is the resistance of the tube or junction associated with the n-th individual noise source.

The decrease in the noise amplitude with device length is consistent with Hooge's law, where $A \sim 1/N$. However, since the resistance of the CNT film device is given by $R = \rho L / Wt$, where N scales with the device volume, i.e. $N \sim LWt$, A/R is expected to scale as $A/R \sim L^{-2}$. For $W > 2$ μm A is inversely proportional to W ($\sim W^{-1.1}$). For $W < 1$ μm there is a strong power-law relationship between A and W ($\sim W^{-5.6}$). This shows that the variation of resistivity has a strong effect on the noise. The authors demonstrate that the flicker noise amplitude depends strongly on the resistivity, following a power-law relationship with resistivity near the percolation threshold after properly removing the effect of device dimensions. The data obtained strongly suggest that transport peculiarity in the CNT network due to tube-tube junctions, and not the nanotubes themselves, dominate the overall CNT film 1/f -noise. Thus, the 1/f -noise is very sensitive measure of percolation transport in CNT networks.

4.4 Noise power as a function of the network morphology
The noise analysis can be used for characterization the internal structure of the CNT film. The study of relationship between the noise power of CNT nanowire network and the

network morphology was performed by Zhou et al. (2008). A thin film of a CNT network is mapped into a resistor network containing tunneling junctions that are randomly switched. The junctions can be branching or touching, therefore they have internal structures. The $1/f$ -noise spectra results from the superposition of a large number of Lorentzian spectra corresponding to unstable junctions between CNTs due to random structure of the film. A possible mechanism for instabilities of the junctions is local trapping sites with occupation number affecting the junction resistance. When the junction resistance is small, the fluctuation in current noise is large due to increased influence from switching on a junction. It is shown that the noise power scales with the average current in a power law $S \propto I^{-\omega}$, where ω is a function of the network morphology.

Thus the authors found that the total noise power and its relation to the current and junction resistance are most useful macroscopic quantities that contain information of the microscopic geometric structure of the CNT network.

5. Noise characteristics of the FETs based on parallel aligned CNTs

5.1 Omitting of noise due to crossover and misalignment

Using parallel aligned CNTs it is possible to remove crossover among CNTs and reduce noise level by removing the noise generated by tube-tube junctions. In (Lee et al., 2010) developed a wide contact structure for low-noise nanochannel devices based on a CNT network. This low-noise CNT network-based device has a dumbbell-shaped channel, which has wide CNT/electrode contact regions and, in effect, reduces the contact noise. It is established an empirical formula that can explain the noise behavior of arbitrary-shaped CNT network-based devices including the effect of contact regions and CNT alignment. Analysis revealed that the noise amplitude of aligned CNT networks behaves quite differently compared with that of randomly oriented CNT networks. In back-gate FETs where most of the surface area of the nanorod is exposed to the ambient, the surface states could be the major noise source via random walk of electrons for the $1/f$ -noise. In dual gate transistors, the interface states and oxide traps can compete with each other as the main noise source via random walk and tunneling, respectively.

The charge transport and noise properties of three terminal, gated devices containing multiple single-wall metallic and semiconducting CNTs were measured at room temperature and the relative low-frequency excess noise of the metallic tubes was observed to be two orders of magnitude lower than that of the semiconductor tubes (Reza, et al., 2006). The low-frequency current NSD in five arc-discharge-grown MWNTs have been recorded at temperatures of 295K, 77K, and 4.2K, and find that the noise decreases moderately with temperature (Tarkiainen et al., 2005). At 4.2K, instead of the usual $1/f$ -type of spectra, authors observe Lorentzian line shapes resulting from one or a few systems of two-level fluctuations. Analyze of these spectra in terms of resistance fluctuations ΔR and obtain $\Delta R = 1\text{k}\Omega$, most likely caused by changes in the contact resistance. Single CNTs approximately 20 nm in diameter and 1 μm in length, were positioned across a gap between two wide, and pre-patterned gold electrodes. At 295 and 77 K the NSD can be accounted for by the Eq. (5) and the values of exponents β and γ are given in Table 1 for the 5 samples.

Sample	R_{295K} (kΩ)	$S_I(295K)$ (pA²)/Hz	γ_{295K}	β_{295K}	R_{77K} (kΩ)	$S_I(77K)$ (pA²)/Hz	γ_{77K}	β_{77K}	R_{4K} (kΩ)	$S_I(4K)$ (pA²)/Hz
1	33	8	1.07	2.28	53	6	1.03	2.00	55	1
2	390	40×10^3	1.09	1.76	2450	2×10^3	1.09	1.54	620/910a	300
3	133	200	1.15	2.04	801	8	1.16	2.12	275	1
4	-	-	-	-	70	20	0.94	1.87	106	1
5	13	90	1.07	1.93	26	20	b	1.79	49	4

aThe differential resistance is asymmetric with respect to the current direction.
bThe experimental value was not determined. $\gamma = 1$ was assumed for extrapolation.

Table 1. Exponents β and γ, and inter-extrapolated NSD at $f_0 = 100$ Hz and $I = 100$ nA (Tarkiainen et al., 2005)

The linear resistance is given for 295 K and 77 K, while the 4 K value is the differential resistance at 100 nA. It is clear that $\beta = 2$ is expected for pure resistance fluctuation in ohmic conductors. The $\beta \neq 2$ behavior is associated with nonlinear characteristics, and the fact that $\beta < 2$ suggests that S_I/I^2 scales proportionally to the resistance. At the temperature 4.2 K found that the 1/f-structure of Eq. (5) cannot account for the data anymore. Instead, the measured noise spectra are composed of a sum of a few Lorentzian line shapes (Tarkiainen et al., 2005):

$$S_I = I^2 \sum \frac{S_L^{(i)} \tau_i}{1 + (2\pi\tau_i f)^2} , \tag{20}$$

where each Lorentzian is characterized by a lifetime τ_i and an amplitude $S_L^{(i)}$. Those Lorentzians are found to depend on the bias voltage, which leads to irregular and nonmonotonic current dependence of the noise. According to the generic 1/f-model, the individual fluctuations are thermally activated, and freeze out, as the temperature is lowered. The two parameters characterizing an individual fluctuator, the magnitude S_L and the life time τ, were both found to depend on the bias current. It is found that the level of LF excess noise decreases by a factor of 10–100 when temperature is lowered from 300 to 4 K. At 4.2 K, single fluctuators play a significant role in the noise behavior of NTs. A model with exponentially current-dependent time constants was utilized to explain the measured current noise spectra, reminiscent of findings in tunnel junctions. It is find the metal–CNT contacts are a likely source for these fluctuations. Eventually, so few sources are left that they show up as individual Lorentzians. The noise scales as

$$S_I \propto kD(\tilde{E}) . \tag{21}$$

Here $D(E)$ is the distribution of the activation energies and

$$\tilde{E} = -kT \ln(2\pi f \tau_0), \tag{22}$$

where τ_0^{-1} is the attempt frequency (Dutta & Horn, 1981). Assuming weakly energy-dependent $D(E)$, the examined samples in (Tarkiainen et al., 2005) full quite close to this model. Using value $A = S_I f / I^2$ one can obtain at 295 K $A = 8 \times 10^{-8} \div 4 \times 10^{-4}$. This is comparable to $A = 3 \times 10^{-7}$ reported for a MWNT (Ouacha et al., 2002). Appenzeller with co-workers reported a substantial noise reduction for a tube transistor with multiple carbon nanotubes in parallel (Appenzeller et al., 2007). An intriguing experiment of detection molecules as additional scattering sources using noise properties of CNT-FETs based on aligned in parallel CNTs has been demonstrated in (Xu et al., 2008). The results are important for future sensors developments.

Thus, in this section we discussed how current in a CNT transistor is determined by the injection of carriers at the electrode/CNT interface, while at the same time excess noise is related to the number of carriers inside the CNT channel. It is demonstrated a substantial reduction in noise amplitude for a tube transistor with multiple CNTs in parallel.

5.2 Reduced influence of parasitic conduction channel

Decreasing the Schottky barriers and in the ideal case obtaining ohmic contact at the contact regions will allow the intercontact distances to be reduced simultaneously using the advantages of channel transport phenomena with different surface modified conditions in CNTs. Therefore the study, modification and optimization of conductivity in CNT-FETs has recently become an important research topic. One of the most effective methods for modifying material properties and interface states is gamma radiation treatment. Very interesting effects of treatment are observed after gamma irradiation at small doses for conventional semiconductor devices. During increasing accumulation dose, regions of certain radiation doses can be found, where the structural and electrical parameters of materials can be improved due to radiation-stimulated diffusion process and the structural ordering of native defect structures and strain relaxation effect.

We investigated the influence of γ-radiation with several small doses of radiation treatment of single-walled carbon nanotube FETs (Fig. 12) by using a ^{60}Co source (Vitusevich et al., 2009). Noise spectroscopy is used to extract additional important information about the mechanisms of transport formation in the multilayer structure of FETs before and after gamma radiation treatment. In the structures under test typically 500-600 nanotubes were found to be connected in parallel between the contacts using scanning electron microscope. It will be shown below that such a structural design with a sufficiently large length between the contacts allows effective current control through the CNTs of FET structures rather than the contact resistance. A standard isotope ^{60}Co source was used to emit characteristic gamma rays with a flux of 1 Gy/s and energy of 1.2 MeV. Gamma irradiation results in the trapping of holes in the SiO_2 near the Si/SiO_2 interface and the creation of interface states at the Si/SiO_2 boundary. High-quality Si/SiO_2 structures have pre-irradiation interface trap densities in the range of 10^9-10^{10} traps/cm². In the bulk of the oxide film, the silicon ionization and the interstitial oxygen donor centers are shown to be responsible for the radiation-generated positive space charge build-up (oxide charge) in thermally grown silicon oxide. Usually non-recombined holes remain initially close to their points of creation and cause a negative shift of the flat band voltage and the threshold voltage. Holes created by gamma irradiation result in decreasing summary resistance.
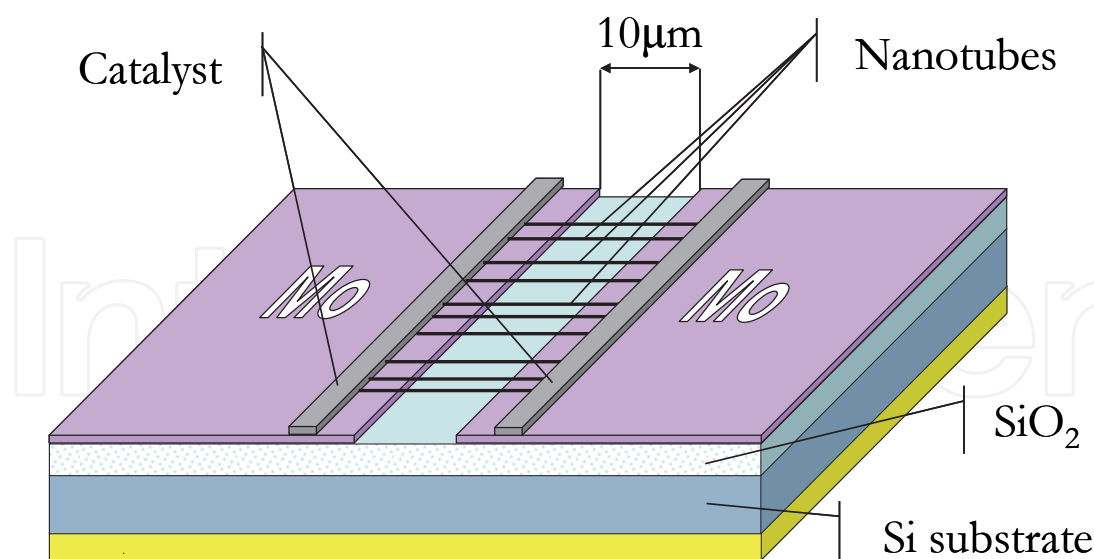
Fig. 12. Schematic of the investigated CNT-based FETs

In the investigated CNT FET structures, it was not observed any shift in threshold voltage or decrease of the summary resistance after a small dose of gamma radiation of 1×10^4 Gy. Moreover, increasing summary resistance was registered. This fact demonstrates that the main changes in transport properties after gamma radiation treatment are related to channel conductivity determined by CNTs. The origin of this modification can be explained by a slight modification of surface atom ordering in CNT due to the introduction of vacancies and interstitial point defects. In addition, the change in drain current before and after gamma radiation was found to be independent on gate voltage. The fact demonstrates that the radiation treatment removed a resistance parallel to the nanotubes. The results of noise spectroscopy give additional important information about the processes and mechanisms of transport formation in the structure. An analysis of the current noise power spectra allows confirming that the main noise source is caused by transport phenomena in carbon nanotubes.

After gamma irradiation this flicker noise component shifts to the lower frequency range (Fig. 13) and demonstrates decreased changes with V_G. It is known that the relative noise level in different kinds of materials can be estimated according to the Hooge relation as follows:

$$\frac{fS_I}{I^2} = \frac{\alpha_H}{N} .$$ (23)

The substitution of the total number of carriers that can be found as $N = \dfrac{L_{DS}^2}{e\mu R_N}$ into Eq. (23)

yields:

$$\alpha_H = \frac{fS_I L_{DS}^2}{I^2 e\mu R_N} ,$$ (24)
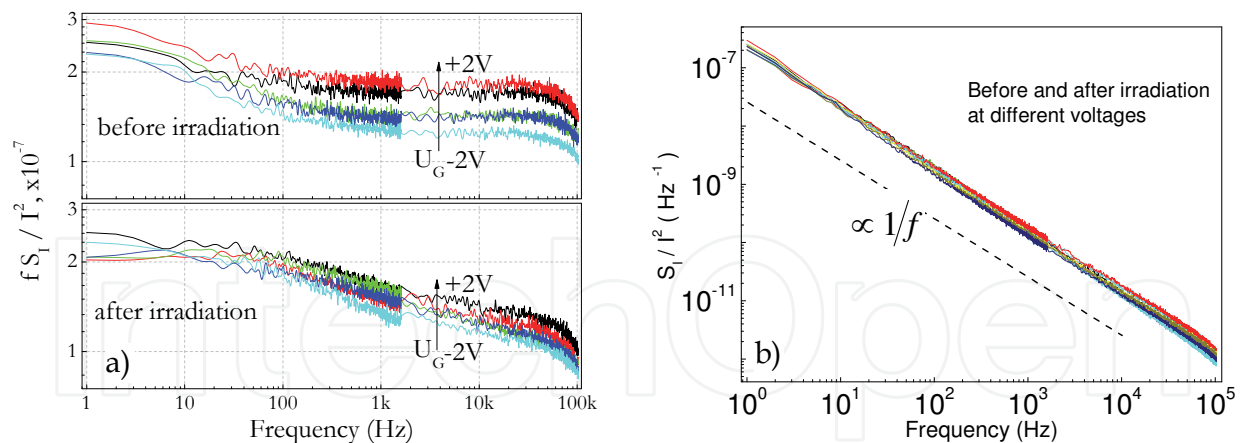
where R_N is the resistance of carbon nanotubes.

Fig. 13. Normalized current noise power spectra of CNT-FETs (a) measured before and after irradiation with a dose of 1×10^4 Gy at different V_G in the range from -2V to 2V with step 1V and V_{DS} =30 mV; (b) Noise power spectra measured at different V_G and constant V_{DS} and vice versa before and after gamma radiation treatment, demonstrating 1/f-noise dependence.

If the current I drops due to the mobility μ decreasing then value of fS_I / I^2 increases by 1.3 times and this result in the increase of α_H. In the spectra of the low-frequency range, the noise level at $f = 1$ Hz also increases by about 1.3 times. This fact confirms the suggestion that the noise in CNT is caused by defects introduced by gamma radiation. Taking into account the measured value of mobility 1.5x10⁵ cm²/Vs and Eq. (24) one can obtain the Hooge parameter as α_H =3.8x10⁻³ before gamma irradiation and 5.3x10⁻³ after irradiation. This low value of the parameter is even better than the values obtained previously for carbon nanotube samples with a long length of the tube without gamma irradiation treatment and is comparable with those of conventional semiconductors such as GaAs, GaN, Si, which indicates the low noise level of the carbon nanotubes themselves. We found for the 1/f -noise component that the dependence on gate voltage at increasing V_G from -2 V to +2 V noise level increases 1.25 times and the current decreases 1.11 times. Such noise behaviour is approximately the same before and after gamma irradiation. According to Eq. (24), the value fS_I / I^2 increased with decreasing current as $1/I$ in 1.11 times. The remaining 1.13 times can be explained by decreasing in $\sqrt{1.13} = 1.06$ times the active part of the length of the channel. The latter is usually observed in FETs and confirms that the origin of 1/f -noise is not due to the contact noise.

In addition to the flicker noise component, the generation-recombination noise component can be resolved in the low-frequency range of the spectra. The G-R component of the noise spectra can be described by

$$\frac{fS_I^{GR}}{I^2} = \frac{fS_I^{GR}(0)}{1 + (2\pi f \tau)^2}, \tag{25}$$

where S_I^{GR} is the G-R current noise spectral density, and τ is the time constant of the G-R process.

From this part of noise spectra, the numerator increases twofold after gamma irradiation with respect to noise level before irradiation, at the same time the denominator change is caused by decreasing time constant τ as a result of the influence of radiation. It should be noted that the G-R component has weak dependence on gate voltage, but the dependence is nonmonotonous in both cases before as well as after gamma irradiation. The noise spectra after subtracting the $1/f$-noise component demonstrate that the main difference between the spectra is the shift of regions with $1/f^2$-dependence to the higher frequency range. The result indicates that traps with different energy levels were activated as a device was exposed to small doses of gamma radiation. At the same time, the noise level has approximately the same value for both cases and the concentration of the traps does not change very much at this low exposure dose.

In addition, the results of transport and noise measurements obtained after gamma radiation treatment with a dose of 2×10^4 Gy confirm such a behaviour. The level of normalized current noise power spectra was found to be independent on drain and gate voltages. The experiments rule out any predominant contribution from the contacts and confirm that the main source of noise in the structure is related to the transport phenomena in CNTs.

Thus, the analysis shows that the difference in output characteristics of the FETs before and after small doses of gamma radiation treatment is due to a reduced contribution to the total current parallel to the nanotube resistance. The transconductance of the CNT-FETs and level of noise did not change strongly after γ-irradiation at a dose of 1×10^4 Gy and 2×10^4 Gy. The results show that active γ-radiation treatment can improve the transport and noise properties of CNT-FETs at some small optimal dose. The radiation treatment was found to decrease the influence of parasitic conduction channels on DC characteristics of the device. The Hooge parameters obtained are comparable with typical values obtained for conventional semiconductors.

6. Shot noise as a probe of elastic and inelastic transport phenomena

In this section we briefly describe and emphasize an importance of shot noise studies. The shot noise allows analyzing discrete carrier motion with different correlation degree induced by collective phenomena in mesoscopic transport. Poisonnian shot noise $S_I = 2eI$ is usually registered when temperature is decreased and transport is determined by an uncorrelated stochastic process. At the same time if electron –electron process becames correlated due to interactions such as Coulomb repulsion or resulting from Pauli Exclusion Principle, then shot noise can be suppressed. In the case of enelastic scattering process the shot noise can be increased. The degree of correlation process can be described by Fano factor, F, represented the ratio of the measured noise power spectral density S_I to the full shot noise value: $F = S_I/2eI$.

Using shot noise measurement in SWNTs at high bias, Wu and co-workers found strong suppression of noise with increasing voltage and determined the electronic temperature (Wu et al., 2010). The authors show that this temperature is in good agreement with phonon one, obtained by Raman spectroscopy. The fact allows concluding that optical phonons and electrons are nearly at the same temperature and standard heat flow model with typical electron-phonon coupling parameters can be applied for the SWNTs. For electron transport

throught a quantum dot and defect free CNTs shot noise can be either suppressed or enhanced with respect to the Poissonian value (Onac et al., 2006; Betti et al., 2009). If the barriers are symmetric, the resonant charge state is occupied 50% of the time and a $F = 1/2$ shot noise suppression is predicted. Onac with co-workers found, that depending on the tunneling rate through the excited state and the relaxation rate two tunneling regimes can be distinquished (Onac et al., 2006). For inelastic cotunneling super-puassonian noise $F > 1$ (but smaller than the maximum $F = 3$ predicted value) was measured for the first time, while elastic cotunneling leads to Poissonian noise $F = 1$. Shot noise with interaction effect was found in SWNT (Wu et al., 2007; Herrmann et al., 2007) as a result of asymmetric Fabry-Perot resonances. Kim et al., 2007 studied also shot noise in the Fabry-Perot regime in ballistic SWNT and obtained power law dependence at low bias voltages as well as reduced conductance oscillations at larger bias. The measurements constitute the first quantitative investigation of a Tomonage-Luttinger Liquid interaction effects in the shot noise of SWNTs. Roche with co-workers studied noise properties in suspended ropes of single wall CNTs in wide temperature range at different currents (Roche et al., 2002). The effect of strong shot noise reduction was explained by correlation between the current noises in different tubes. The charge and spin transport was theoretically analysed using shot noise in single-walled CNT weakly coupled to metallic leads: ferromagnetic and nonmagnetic (Weymann et al., 2007). It has also been shown that Fano factor in the antiparralel configuration is typically larger that the Fano factor in the parallel one. The spin-dependent rectification of the current caused by asymmetry was registered experimanttally in the CNTs contacted with one ferromagnetic and one normal-metal electrode (Merchant et al., 2008). The authors also observed a significant periodic reduction in the current shot noise, explained by increased spin-flip rates at sertain gate volgates.

7. Conclusion and outlook

Carbon nanotubes represent a novel material for development of field-effect transistors with characteristic sizes considerably smaller compared to conventional down-scaled silicon transistors. Thus, CNTs offer new perspectives due to the high degree of ordering of carbon atoms on the surface of the tube, which serves as very uniform channel for high-speed electron transport. The study of noise properties in CNT materials and CNT-FETs is proved to be expremely sensitive method for basic research. It has been illustrated that noise can be used to investigate transport phenomena and factors determining the transport: influence of contact interfaces, dielectric-nanotube interactions, effect of different surroundings. Noise spectra demonstrate high sensitivity to percolation transport and network morphology, to external gamma radiation treatment, to collective phenomena, like in the case of a Tomonage-Luttinger Liquid interaction effects. Noise-enhanced signal processing at the nanolevel promises applications to signal detection in wideband communication systems, biological and artificial neural networks. Investigations of LF noise provide better understanding of physical processes taking place in the bulk region, on the interfaces and on the surfaces of nanotubes and their role in the low frequency noise origin.

- LF noise spectral density can be described as

$$S_V = A \frac{V^{2+\beta}}{f^\gamma}.$$

- Parameter A generally reflects the sample quality and increases with decreasing device size and depends on many parameters of material, its structure, sizes, CNT's bulk and surface physical and chemical conditions, from its fabrication method. The noise amplitude

$$A \propto R, \quad A \propto \frac{1}{N}, \quad A = \frac{\alpha_H}{N}, A \propto \frac{1}{L},$$

R is the device resistance, N is the number of atoms or carriers in the system, L is the sample length ($N \propto L$). $A = 1.0 \times 10^{-11} R$. Parameter A varies within 10^{-13} up to 4×10^{-4}.

- Parameter $\beta = 0$ is expected for pure resistance fluctuation in ohmic conductors. The $\gamma \neq 1$ behavior is associated with nonlinear characteristics. Usually $|\beta| << 1$, $|\Delta\gamma| << 1$ are material dependent numbers ($\gamma = 1 + \Delta\gamma$).

- Excess noise with a slope different from unity ($\gamma \neq 1$) can be explained by a superposition of a few Lorentzians and of the 1/f-noise. The change in slope with respect to temperature is thus explained by the variation of trap activities. A value of close of 1 for γ indicates that the origin of the measured noise is conductance fluctuations; a value of 1.5 for γ suggests a diffusion process between two different media.

- Tersoff proposed the alternative "charge-noise model", which was successfully proved on the SWNT-FETs affected by random fluctuation of charge in different environments.

- Investigation of noise sources and its behaviour will be source for determination and explanation of physical processes in nanotubes and will help one to suggest noise reduction method nanotube's based devices.

Nanotubes are promising candidates for advanced nanoelectronic devices, and they have great potential in a wide range of applications, such as FETs, elementary logic circuits, bio- and chemical sensors, nanotechnology, biotechnology, electronics, memory devices, optics and other fields of materials science, as well as potential uses in architectural fields.The pronounced noise level observed in CNT devices simply reflects the small number of carriers involved in transport. These results not only provide the basis to quantify the noise behavior in a 1D transport system but also suggest a valuable way to characterize low-dimensional nanostructures based on the 1/f-fluctuation phenomenon. Noise spectra can be applied to several types of challenges:

- Determination of noise parameter A or patterns that characterize the dynamics or structural features of CNTs;
- Transport phenomena of individual CNTs,
- Percolation transport and novel phenomena in CNT-FETs fabricated based on CNT thin films,
- Determination of flow dynamics in distributed systems based on the analysis of dynamic correlations in stochastic signals which are simultaneously measured at different points in space,
- Registration of environmental changes and identification of molecular objects, also at the level of single molecule.

Studies on nanoscale FET sensors reveal the crucial importance of the LF noise for determining the ultimate detection limit. In this respect, the noise results have been

highlighted some future directions for CNT-FETs technology. As a big challenge one has to face the synthesis of parallel aligned CNTs with well defined type of conductivity. This is particularly important for the LF noise suppression and increasing of SNR. Technology and understanding of the contact-CNT interface remains an important issue for further studies. Controlled doping of the contacts may provide one of the methods of the problem solving. It has been shown that CNTs and CNT-FETs are especially promising for sensing applications. Compared to conventional FETs, nanoscaled devices provide a larger surface-to-volume ratio. This results in a high sensitivity of the overall FET channel conductance to changes in the surface potential caused by the adsorption of molecules. In order to reach the detection limit, intense attempts have recently been made to understand the factors determining the SNR. Studies on CNT-FETs showed that the SNR considerably increases in optimal operation regime. Biomolecules and biological object contain as backbone carbon atoms. Therefore interfacing living systems with nanocarbon materials is promising direction for biosensor applications. One may anticipate a broad scope of noise spectroscopy applications in the area of bioanalytic and advanced material research.

8. References

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Carbon Nanotubes Applications on Electron Devices

Edited by Prof. Jose Mauricio Marulanda

Carbon nanotubes (CNTs), discovered in 1991, have been a subject of intensive research for a wide range of applications. In the past decades, although carbon nanotubes have undergone massive research, considering the success of silicon, it has, nonetheless, been difficult to appreciate the potential influence of carbon nanotubes in current technology. The main objective of this book is therefore to give a wide variety of possible applications of carbon nanotubes in many industries related to electron device technology. This should allow the user to better appreciate the potential of these innovating nanometer sized materials. Readers of this book should have a good background on electron devices and semiconductor device physics as this book presents excellent results on possible device applications of carbon nanotubes. This book begins with an analysis on fabrication techniques, followed by a study on current models, and it presents a significant amount of work on different devices and applications available to current technology.

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