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by

SHAHED REZA
Dedicated to
My mother
Nurunahar Tahera
And my father
ATM Naderuzzaman Talukdar
ACKNOWLEDGMENTS

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EXCESS NOISE IN ONE DIMENSIONAL QUANTUM NANOWIRES
By
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Silicon nanowires and carbon nanotubes are two promising novel devices in the nanotechnology area. A study of the current-voltage and the low frequency excess noise properties of these devices is presented.

From the silicon nanowire current-voltage and noise characteristics measured at room temperature in the linear regime of device operation, the bulk and contact resistance contributions are extracted and modeled. The excess noise observed at low frequencies is interpreted in terms of bulk and contact noise contributions, with the former comparable, in terms of Hooge parameter values, to the low noise levels observed in high quality silicon devices. The contact noise is significant in some devices and is attributed to the impinging end of the bridging nanowires.

The charge transport and noise properties of three terminal, gated devices containing multiple single-wall metallic and semiconducting carbon nanotubes were measured at room temperature. A method to separate contributions from the metallic and semiconducting carbon nanotubes by sequential ablation using high voltage pulsed bias is
presented. 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.

The low frequency noise of single-walled carbon nanotubes is studied over the 77K to 300K temperature range. Lorentzian shaped spectra along with 1/f noise spectra have been observed. From the Lorentzian noise components, a range of thermal activation energies from 0.08 to 0.51 eV for the associated fluctuation mechanisms is obtained. From the 1/f noise spectra, a distribution of activation energies of fluctuation processes ranging from 0.2 to 0.7eV is derived. These findings indicate that the observed noise spectra are caused by number fluctuations. Using simulation results and the observed gate dependence of the noise producing activation energy distribution, the physical origin of the observed noise phenomena was shown to be the contact region.
CHAPTER 1
INTRODUCTION

In the last decades of the 20th century there has been a remarkable progress in electronics. The technology that has been the vehicle of this revolution is the complementary metal oxide silicon field effect transistor (CMOSFET or CMOS). Since the introduction of this technology the basic device remained mostly unchanged, but the device size gradually became smaller. This miniaturization enabled semiconductor industries to pack more devices in a chip, thus increasing the functionality, speed and cost reduction. Over the last three decades this miniaturization trend continued in a very consistent manner, roughly every three years quadrupling the packing density, obeying Moore’s law. There are strong indications that the limit of the miniaturization is rapidly approaching. The current state of the art MOS device has a feature size of 20nm and the physical limit for scaling is expected to be ~10nm. Below this feature size the error in the lithography and the uncertainty of the doping profile will be a great obstacle for manufacturing high performance devices [1]. Unless a new technology is discovered, the semiconductor industry faces the danger of becoming stagnant. This necessitates the research for device structures that may take the place of the current CMOS technology. Several new devices have been proposed. Among them, ferromagnetic field effect transistors, single electron transistors, molecular transistors, silicon nanowires and carbon nanotubes are currently in the forefront of research.
Figure 1-1. Carbon nanotube and the planer graphene sheet (Image courtesy of Dr. Ant Ural, Dept. of ECE, University of Florida).
Carbon nanotubes (CNT) were discovered by Iijima in 1991 [2]. The arrangement of atoms in a CNT is the same as the atomic arrangement in graphite. A CNT can be described as a graphene sheet rolled on to itself and forming a hollow tube [3] (see Fig. 1-1). The ends of the nanotube can either be open or capped by the so-called Fullerenes, a half sphere structure [4]. CNTs can be either single walled or multi-walled. The diameter of a single wall CNT generally is between 0.7 to 10nm and its length can vary from nm to µms depending on the growth conditions. Because of the small diameter CNTs operate as one-dimensional quantum structures. Furthermore, the CNTs can be grown and the critical feature size, the diameter, is determined by the growth process and thus, unlike in MOS technology, does not depend on lithography. This is a significant advantage of CNTs over the current CMOS technology.

The carbon nanotube is a unique device. First, the CNT can be either metallic or semiconductor, so it can potentially be used both as the device and the interconnects. Furthermore, the band-gap of the semiconducting tube depends on the diameter. This can potentially eliminate the need for complex band-gap engineering and there are many possible ways this property can be utilized. CNT is a very good conductor of heat and current; the current density of CNTs can be orders of magnitude higher than copper [5]. The carbon nanotube is a very stable structure having a tensile strength of about 60 times greater than steel [6]. Despite these very attractive properties, there remain several significant obstacles before the CNT technology can be considered for mainstream electronics.

The fabrication method of CNT is still far from perfect. During the CNT growth process a mixture of CNTs of different length, diameter and orientation is formed. The
process to selectively grow a CNT with a certain feature size at a precise location is still unknown. Another problem, first reported by Collins et al. [7], is high excess noise. One would expect lower excess noise levels since the atoms in a graphene structure are well ordered and properly terminated. On the contrary the 1/f like noise in CNTs was observed to be extremely high. Compared to a carbon film resistor, which is generally considered too noisy for many applications, CNT is several orders of magnitude more noisy. Unless a way to reduce this noise is found, the applicability of CNTs in mainstream electronics will be severely limited.

Collins et al. [7] observed that both single-wall and multi-wall CNTs are equally noisy. The observed excess noise obeys the well-known expression for 1/f type noise,

\[ S_{1/f}(f) = \frac{A \cdot f_{dc}^\beta}{f} \]

where \( I_{dc} \) is the dc current level, \( f \) is the frequency, and \( A \) and \( \beta \) are constants. The exponent \( \beta \) was found to be approximately equal to one as expected for 1/f type noise. The parameter \( A \) represents the relative magnitude of the 1/f noise.

Additionally, Collins et al. established the following empirical relationship between the 1/f noise coefficient \( A \) and the resistance of the device \( R \),

\[ A/R \approx 10^{-11} \text{S} \]  

(1-2)

Recently, Snow et al. [8] reported an additional dependence in (1-2) for a two dimensional network devices or mats,

\[ A/R = \frac{9 \times 10^{-11}}{L^{1.3}} \text{S} \]  

(1-3)

where \( L \) is the device sample length in \( \mu \text{m} \) and which may be longer than the length of the constituent CNTs. A reduction in 1/f noise with device length is expected for an
electronic system where 1/f noise varies inversely with the number of carriers, but the fact that $A/R$ is inversely proportional to $I/L^{1.3}$ cannot be explained from the number of carriers; normally one would expect a $I/L^2$ relationship. Snow et al. also reported on 1/f noise gate voltage dependence. The noise magnitude is minimum at 0V gate bias and maximum at the gate voltage where the device inverts from p-type to n-type mode of operation. Furthermore, it was reported that at positive gate voltage the resistivity fluctuation $S_\rho$ is related to the resistivity $\rho$ by

$$S_\rho \propto \rho^{3.6}. \quad (1-4)$$

This type of power law dependence is characteristic of percolating systems. And in fact the two-dimensional mats used by Snow et al. resemble a percolation system [9] where the device consists of many interconnected CNTs. Unlike a conventional one-dimensional device, where a carrier flows from one contact to the other ballistically through one CNT, in these devices the carriers flow through the multiple intersecting network of CNTs. This can result in a length dependent transport properties and it is the likely cause of the $I/L^{1.3}$ dependence shown in (1-3).

In an attempt to exclude possible noise from the contact, Collins et al. [7] conducted a four-point probe measurement, but did not observe a change in the measured noise between a two- and four-point probe experiments. Hence, they concluded that the source of the noise is not the contacts. However, now it is understood that a four-probe technique cannot be used for carbon nanotubes, because the contacts are an integral part of the mesoscopic CNT device and the addition of another set of contacts completely changes the device itself [10]. Hence, the result of the four-probe measurement does not rule out contact as a potential source of 1/f noise. Recently Kingrey et al. [11] reported
the effect of annealing and passivation studies. It was observed that after annealing, the
noise magnitude of a CNT at room temperature decreased but it was still substantial and
varied widely across the temperature range of 80 to 450K. In an attempt to prevent
absorption of species back on to the CNT after heating, two different types of passivation
layers, SiO2 and Polymethylmethacrylate, were tried. In both cases no significant change
in noise characteristics was observed. In the same study the presence of Lorentzian
spectra along with 1/f noise was reported.

The presence of Lorentzian spectra is also reported by Tarkiainen et al. [12]. The
observed Lorentzian spectra can be expressed by the following expression [13],
\[
S_L(f) = \frac{S_L(0)}{1 + \omega^2 \tau^2},
\]
where \(S_L(0)\) is the plateau value of the Lorentzian, \(\omega\) is the angular frequency and \(\tau\) is a
characteristic time. This type of noise spectra is associated with a two energy level
system. The characteristic time of the observed spectra was found to be a function of the
bias voltage. Most importantly, the noise characteristics were observed to be dependent
on the direction in which the bias was applied, which may correspond to the location of
the trap centers.

The exact mechanism of the 1/f noise phenomena in general is still unclear.
However, two widely accepted models for this phenomenon exist. The first one proposed
by McWhorter [14] was successful in explaining the noise in MOSFETs. This model
assumes that the noise is caused by carrier number fluctuations. The second model,
proposed by Hooge [15], postulates that the 1/f noise phenomena originates in the bulk
because of mobility fluctuation of carriers. Hooge’s model requires the exponent \(\beta\) in (1-1)
to be exactly 1; however McWhorter’s model does not have this restriction.
Commonly, the Hooge’s parameter $\alpha_H$ is used as a figure of merit to compare the $1/f$ noise levels between devices and technologies even if the source is of McWhorter type. This figure of merit $\alpha_H$ is related to the $1/f$ noise coefficient $A$ by

$$\alpha_H = A \cdot N$$  \hspace{1cm} (1-6)

where $N$ is the number of carriers associated with the fluctuation process.

Ishigami et al. [16] in their recent publication addressed the issue of which mechanism is responsible for the observed $1/f$ noise. They established that the $1/f$ noise parameter $A$ is inversely proportional to the number of carriers $N$. Since

$$N = c_g L |V_g - V_{th}| e $$  \hspace{1cm} (where $c_g$, $L$, $V_g$ and $V_{th}$ are gate capacitance, device length, gate voltage and gate threshold voltage respectively), it follows that

$$\frac{1}{A} \propto |V_g - V_{th}|. \hspace{1cm} (1-7)$$

Based on (1-7) Ishigami et al. concluded that the noise is of the mobility fluctuation origin. Their argument is based on a bulk MOSFET analogy where equation (1-7) is true only if the noise has a mobility fluctuation origin. For a number fluctuation origin one would expect $\frac{1}{A} \propto |V_g - V_{th}|^2$ relationship. Although this statement is shown to be true for MOSFETs, it is not clear whether it would be applicable for a CNT device, because, unlike a MOSFET where the device operation is controlled by the modulation of the channel conductance using gate voltage, for a CNT device the control is achieved by modulating the Schottky barriers formed at the contact region. In addition, CNT devices typically have a very significant contact resistance which dominates the current voltage characteristic, and this further complicates the analogy with a simple MOSFET $1/f$ noise model.
Ishigami et al. estimated the value of $\alpha_H$ to be $(9.3 \pm 0.4) \times 10^{-3}$, which is much lower than the previously reported value of $\sim 0.2$ by Collins et al. [7]. This is also supported by a recent publication by Lin et al. [17]. Their estimate for $\alpha_H$ is $2 \times 10^{-3}$. Lin et al. also established that $A$ is inversely proportional to the device length, which is consistent with the $\frac{1}{A} \propto N$ behavior. The findings of Lin et al. further suggested that 1/f noise in CNTs is not substantially affected by the acoustic phonon scattering or ionized impurity scattering. To understand the effect of contact and bulk Lin et al. added a third gate to modulate the bulk region of the device. The 1/f noise level in this modified device also showed similar dependence on device resistance as a conventional device. In this case the measured relative noise magnitude supported the $\frac{1}{A} \propto N$ model established for a conventional device.

In summary, the CNT exhibits thermal, shot and low frequency excess noise. The thermal and shot noise have been characterized and modeled satisfactorily [18]. The 1/f noise magnitude in a CNT is several orders of magnitude higher than in the conventional silicon devices and the origin and mechanism of this noise component are still unclear.

Now the silicon (Si) nanowire devices used in our study will be introduced. Silicon nanowire (SNW) is another leading candidate in the nanotechnology research arena. Similar to CNTs, these devices have a large length over diameter ratio. SNWs are grown; thus, like a CNT, the need for lithography is eliminated. The major advantage of SNW over CNT technology is the constituent material. Si is the material of choice for the mainstream semiconductor industry. As a result, integrating SNW in currently available processes would be easier than the CNT technology.
Figure 1-2. Scanning electron microscope (SEM) image of silicon nanowires connecting two electrodes.
Currently available SNWs typically have a larger radius than the CNTs. The typical SNW radius is on the order of ~50nm, and the radius of a typical CNTs is on the order of ~1nm. Although there has been theoretical work done on the noise of nanowires [19-22], no experimental work has been reported on the noise in SNW. The result of our study on Si nanowires presented in this manuscript will help fill the void.

In this dissertation, the result of a study of the low frequency excess noise of CNT and Si nanowires is presented. Chapter 2 describes the fabrication methods and sample geometry used in this study. In chapter 3 the details of device operation, DC measurements and in chapter 4 the details of noise measurement techniques are discussed. In chapter 5 the results and analysis of the noise measurements on SNWs and the possible source of the observed noise are discussed. In chapter 6 a sequential ablation technique to determine the characteristics of individual CNTs is presented. The analysis of the thermally activated Lorentzian component of noise is discussed in chapter 7. In chapter 8 the details of CNT simulation technique are discussed. Finally, the analysis of the thermally activated 1/f noise in CNTs and the conclusions resulting from the dissertation work are presented in chapter 9 and chapter 10, respectively.
CHAPTER 2
DEVICE FABRICATION AND MOUNTING

Fabrication of Carbon Nanotubes

The growth method for the devices used in this study is the chemical vapor deposition (CVD) growth method [23]. There are several other methods for growing carbon nanotubes; among them the arc discharge method, [24] and laser ablation method are popular [25]. In the CVD growth method, a substrate with a catalyst (typically Fe, Co or Ni) is placed in a furnace and a hydrocarbon and hydrogen gas flow are added. The hydrocarbon gas acts as the source of carbon. At a high temperature (between 500°C and 1000°C) the hydrocarbon, usually methane, is catalytically decomposed and CNTs are formed. The diameter of the grown CNT is approximately equal to the diameter of the catalyst particles used [26]. The CNT can grow outwards from the catalyst particle while the catalyst particle is attached to the substrate or the nanotube grows in between the catalyst particle and the substrate, with the catalyst particle traveling on the tip of the nanotube. A localized growth of nanotube can be obtained by controlling the placement of the catalyst.

In the case of the devices used in this study, the nanotubes were grown on a silicon substrate with a top oxide layer, typically 600nm thick (Fig. 2-1). The catalyst, 10mg/ml Fe(NO₃)₃·9H₂O particles, was dispersed over the entire surface of the substrate so the nanotube growth occurred over the entire surface. The gas flow rate for both hydrogen and methane was 200sccm [27]. Optical lithography was used to pattern Cr/Pd (sputtered on to the wafer, 5nm/45nm thick respectively) 500µm long electrodes spaced 1µm apart.
(the Pd likely overcoats the edge of the Cr layer so that electrical contact to the nanotubes is via the Pd; see Fig. 2-2).

**Fabrication of Silicon Nanowires**

Silicon nanobridges were grown between electrically isolated electrodes formed from the top silicon layer of (110)-oriented silicon-on-insulator (SOI) substrates [28]. Approximately 1nm Au was deposited on the (111)-oriented sides of the electrodes and annealed in a H$_2$ ambient at 670°C to form nanoscale Au-Si alloy catalyst islands. The structure was then exposed to a mixture of 15sccm SiH$_4$, 60sccm HCl, and 30sccm B$_2$H$_6$ (100ppm in H$_2$) in a H$_2$ ambient at 680°C and a total pressure of 1.3kPa for 30min to grow nanowires bridging between electrodes with a separation of 10µm or less. Note that B$_2$H$_6$ is added to provide p-type dopants in the form of boron. It was found that the doping concentration can be controlled by increasing the partial pressure of B$_2$H$_6$. Since the dopant is incorporated during the growth process as opposed to adding it later using ion implantation, it is expected that the lattice structure of the device will be relatively defect free. As will be shown later, the noise measurement results support this idea. Before nanowire growth, reactive ion etching was used to remove Au catalyst from all areas of the substrate other than the sidewalls. This helped to suppress the uncatalyzed growth of Si between electrodes, ensuring good electrical isolation. Highlights of the fabrication process for the bridging nanowires are illustrated in Fig. 2-4. The dimensions of the Si nanowires used in our experiments were measured using a scanning electron microscope (SEM) and are presented in Table 2-1.
Figure 2-1. Cross-section of the device showing different layers.
Figure 2-2. Top view of the device showing the nanotubes and the electrode layout.
Figure 2-3. SEM image of suspended carbon nanotubes.
Figure 2-4. Illustration of fabrication steps for silicon nanowires; (a) Etching to form electrodes on a SOI substrate (b) Angled deposition of Au catalyst particles and (c) Nanowire growth in [111] direction. SEM image of multiple nanowires bridging across the gap between the Si electrodes shown in (d) [28].
<table>
<thead>
<tr>
<th>Device</th>
<th>Wire 1</th>
<th>Wire 2</th>
<th>Wire 3</th>
<th>Wire 4</th>
<th>Wire 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (cm)</td>
<td>Radius (cm)</td>
<td>Length (cm)</td>
<td>Radius (cm)</td>
<td>Length (cm)</td>
</tr>
<tr>
<td>Wafer 1</td>
<td>a 7.5×10⁻⁴</td>
<td>6.8×10⁻⁶</td>
<td>6.6×10⁻⁴</td>
<td>6.2×10⁻⁶</td>
<td>b 4.1×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>d 7.0×10⁻⁴</td>
<td>6.8×10⁻⁶</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wafer 2</td>
<td>a 3.0×10⁻⁴</td>
<td>6.7×10⁻⁶</td>
<td>3.3×10⁻⁴</td>
<td>7.5×10⁻⁶</td>
<td>b 3.4×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>c 6.0×10⁻⁴</td>
<td>7.5×10⁻⁶</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d 6.3×10⁻⁴</td>
<td>4.2×10⁻⁶</td>
<td>6.5×10⁻⁴</td>
<td>5.0×10⁻⁶</td>
<td>6.4×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>e 8.4×10⁻⁴</td>
<td>4.6×10⁻⁶</td>
<td>1.1×10⁻³</td>
<td>6.0×10⁻⁶</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f 1.0×10⁻³</td>
<td>5.0×10⁻⁶</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>g 1.0×10⁻³</td>
<td>6.3×10⁻⁶</td>
<td>8.5×10⁻⁴</td>
<td>4.2×10⁻⁶</td>
<td></td>
</tr>
<tr>
<td></td>
<td>h 1.0×10⁻³</td>
<td>4.8×10⁻⁶</td>
<td>1.0×10⁻³</td>
<td>4.3×10⁻⁶</td>
<td></td>
</tr>
<tr>
<td></td>
<td>i 1.5×10⁻³</td>
<td>4.7×10⁻⁶</td>
<td>1.1×10⁻³</td>
<td>5.6×10⁻⁶</td>
<td></td>
</tr>
</tbody>
</table>
Mounting of Devices

The silicon substrate containing the devices was mounted on a standard TO-8 package (Fig. 2-5). First a 50 mil alumina substrate with top and bottom gold-plated surfaces was attached to the TO-8 package using silver loaded conductive epoxy. Then the silicon substrate containing the devices was attached on the alumina substrate using the conductive epoxy. This way the silicon substrate is isolated from the body of the package and thus can be used as the back gate. Next the electrodes and the back gate were bonded to the pins of the TO-8 package using a wedge bonder.

Some of the CNT devices were fabricated on Pd only electrodes. For these devices it was not possible to bond to the electrode using the available bonders. Because of the softness of Pd, the Au bond wire would not attach to Pd. Hence, conductive epoxy was used to connect the bond wire to the Pd electrode. First a bond was made on the pin of the TO-8 package, and then the bond wire was cut at an appropriate length so that the wire reached the surface of the electrode. A minute amount of epoxy was then dispensed on the electrode using a fine needle and then the bond wire was carefully pushed into this drop of epoxy using a fine set of tweezers. The epoxy was then cured by baking in an oven at 120°C for 8 to 12 hours.

During our first attempt to measure the CNT devices it was discovered that these devices are extremely sensitive to static electricity. For a noise measurement the pins of the TO-8 package need to be soldered to the measuring equipment. But the soldering process and occasionally the mere handling was enough to destroy these highly sensitive devices.
Figure 2-5. Mounting of the device on a TO-8 package.
To eliminate this problem all of the pins of the TO-8 package were soldered to the body of the package using copper wires before attaching the substrates to the package. In this way both ends of a nanotube in the sample always remain shorted together thus preventing build-up of static charge that may damage the device. After the pins were soldered to the measurement system the wire connecting the pins to the body of the package was removed and measurements were made. The SNW devices did not show a static sensitivity hence, did not require the procedure described above.
DC Characteristics of Carbon Nanotubes

Electronic Structure and Properties of Carbon Nanotube

A graphene sheet is a two dimensional structure of carbon atoms arranged in a honeycomb like formation, one carbon atom at each vertex of the hexagon. A CNT has the same basic structure of graphene but instead of a planer structure, it has a hollow tubular shape. The physical, chemical and electrical properties of a CNT depend on how the CNT was formed from the basic graphene structure.

Consider the graphene lattice presented in Fig. 3-1, a CNT can be formed by cutting along the dotted lines joining them together forming a cylindrical shape. The vector represented by $\overrightarrow{AB}$ is called the chiral vector $C$. The length of the chiral vector defines the circumference of the CNT. The chiral vector can be expressed in terms of the lattice vectors $a_1$ and $a_2$, mathematically,

$$C = na_1 + ma_2$$  \hspace{1cm} (3-1)

where $n$ and $m$ are integers and different combinations of $n$ and $m$ yield CNTs of different chirality (the length and the angle of the chiral vector). The chirality uniquely defines a particular type of CNT $(n,m)$ [29], for example zigzag $(n,0)$ and armchair $(n,n)$ CNTs. The formation of these two types of CNTs are explained in Fig. 3-2.

Typically, the length of a CNT is on the order of $\mu$m and the diameter is on the order of nm. Because of the small diameter the CNT operates as a one-dimensional device.
Circumference vector: \( \mathbf{C} = n \mathbf{a}_1 + m \mathbf{a}_2 \)

Figure 3-1. Nanotube formation from graphene sheet; (a) definition of the unit vectors and (b) the directions of the chiral vector for a (4,2) CNT is shown. (Image courtesy of Dr. Ant Ural, Dept. of ECE, University of Florida).
Figure 3-2. Formation of Zigzag and armchair nanotube from graphene. (Image courtesy of Dr. Ant Ural, Dept. of ECE, University of Florida)
Figure 3-3. E-k diagram of graphene in the first Brillouin zone using the $\pi$-band nearest-neighbor tight-binding model; (a) in 3-dimension, and (b) 2D representation showing the conduction and valence bands (Image courtesy of Dr. Ant Ural, Dept. of ECE, University of Florida).
The energy dispersion relation (\(E-k\) plot) of a CNT can be obtained from the \(E-k\) plot of graphene shown in Fig. 3-3. The \(E-k\) plot for a CNT can only be subsets of the two dimensional plot for graphene, because of the quantization in the circumferential direction [30]. These subsets or the energy band are given by slicing the E-k surface for graphene with vertical periodic parallel planes with a constant spacing. The spacing of these planes is determined by the chirality of the CNT [18]. If, for a CNT, one of these planes intersects the \(K\) points, where the conduction band intersects the valence band, then for that particular CNT, the band gap is zero, i.e. the CNT is metallic. This can only happen if,

\[ |n - m| = \text{multiple of } 3. \]  

(3-2)

If the planes do not intersect the \(K\) points, the CNT is semiconducting. For example, the armchair \((n,n)\) CNT is always metallic, but the zigzag \((n,0)\) CNT is metallic if \(n\) is a multiple of 3, semiconducting otherwise. For the same reason, of a randomly grown collection of a total of \(n\) CNTs, \(n/3\) are expected to be metallic and the rest semiconducting. The energy band-gap of a semiconducting CNT is related to the diameter of the CNT by [18]

\[ E_g = \frac{|n| \cdot a_{C-C}}{d_t} \]  

(3-3)

where \(t\) is the nearest neighbor tight binding overlap energy, \(a_{C-C}\) is the nearest neighbor atomic distance and \(d_t\) is the diameter of the tube.

**DC Characteristics and Measurements**

As mentioned before, the conduction and valence band of a metallic CNT intersects and as a result the resistance of a metallic CNT is independent of the gate bias. The resistance of a metallic CNT can be written as
\[ R_{\text{metallic}} = R_{\text{quantum}} + R_{\text{contact}} + R_{\text{bulk}}. \]  

(3-4)

\( R_{\text{quantum}} \) is the lower limit of resistance for a quantum resistance, equals to 12.9 kΩ per sub-band [31]. \( R_{\text{contact}} \) and \( R_{\text{bulk}} \) are the contact and bulk resistances due to non-idealities present in the device. So, the lower limit for the resistance of metallic CNTs is 12.9 kΩ. The characteristics of a semiconducting CNT are more complicated as the current conduction is a function of the gate bias.

The operation of a semiconducting CNT also depends on the nature of the source and the drain metal contact pads. Typically metals with high work function such as Ti and Pd are used for these contacts. In this case at a low drain-source bias (\( V_{ds} \)) the Fermi level of the contacts lines up close to the valence band. As a result the potential barrier for the holes becomes small but the barrier for the electrons becomes large and hole conduction dominates via tunneling. For this reason a typical CNT FET device (CNFET) resembles the characteristics of a conventional p-channel MOSFET. If a metal with a smaller work function is used, then the Fermi level aligns somewhere between the conduction band (\( E_c \)) and valence band (\( E_v \)), depending on the work function of the metal. Fig. 3-3 shows a case where the Fermi level is aligned at the middle of the band gap. In this case at a gate voltage close to 0V, both electron and holes experience a potential barrier so conduction is negligible (see Fig. 3-4(a)). With increasingly negative gate bias, the width of the barrier for the holes decreases and increasing number of holes can tunnel through (see Fig. 3-4(b)). At a sufficiently high negative bias the barrier is completely removed and the current through the devices becomes independent of gate bias.
Figure 3-4. Qualitative response of the nanotube conduction and valence band at (a) a gate voltage below threshold voltage so that the CNT is off and (b) at a gate voltage above threshold voltage so that the CNT is on [32]
Figure 3-5. Measured drain current vs. voltage characteristics at different gate bias
Because of the symmetry of the Fermi level alignment, electron transport can be achieved with a sufficiently high positive gate, which makes this particular CNT an ambipolar device.

The $I_{ds}$ vs. $V_{ds}$ plot at different gate bias for a typical device used in our study is presented in Fig. 3-5. The plot is almost linear, but with higher $V_{ds}$, sub-linear characteristics were observed in most devices due to phonon dispersion, in few cases super-linear characteristics were observed as well [33]. From the devices studied, each contained a randomly grown matrix of metallic and semiconducting CNTs between the drain and source Pd metal contacts. Fig. 3-5 indicates p-type channel operation and it shows an on-state at $V_g = 0$V gate bias as expected based on the earlier discussion. The device becomes more conductive at increasing negative gate bias and saturates at $V_g = -10$V gate bias. With increasing positive gate bias the conduction decreases because the barrier for hole tunneling becomes increasingly wider. This device does not show ambipolar transport because the gate bias required to lower the barrier enough for electron transport cannot be achieved. A high gate bias is required because the Fermi level is pinned close to the valence band edge and the gate oxide layer in these devices was thick.

The metallic CNTs do not respond to the gate bias, so at a high positive gate bias, when the semiconducting CNTs are off the measured current $I_t$ is the total current through the metallic CNTs $I_m$. With $I_m$ known, at any gate bias the current through the semiconducting CNTs $I_s$, can be calculated from

$$I_s = I_t - I_m.$$  

(3-5)
Alternatively, the total conductance of the semiconducting CNTs can be obtained by subtracting the total conductance of the metallic CNTs (measured when the semiconducting CNTs are off) from the measured device conductance. Plots of the total dynamic (ac) conductance $G_{ac}$ and the metallic and semiconducting components are presented in Fig. 3-6.

The DC characteristics were found to be a weak function of temperature for the temperature range of our experiment 77K to 300K. A plot of the ac conductances at 77K and 300K is shown in Fig. 3-7.

**DC Characteristics of Silicon Nanowires**

**Resistance Measurements**

The SNW devices used in this study have a much larger radius than the CNT devices described earlier, around ~50 nm. As a result, unlike CNTs, these devices do not operate in the quantum domain. The resistance of these devices can be characterized by equation (3-4) with $R_{quantum} \approx 0$. Since, the calculation of the bulk component of the resistance is relatively straightforward, it opens up an opportunity to model the total resistance in terms of bulk and contact components. The details of method employed for this modeling is presented next.

The I-V characteristics of the SNW devices were measured using an HP4145B semiconductor parameter analyzer. The devices were found to be very linear over the voltage range of ±5V.
Figure 3-6. Measured dynamic conductance and the calculated components vs. gate bias.
Figure 3-7. Measured dynamic conductance vs. gate voltage bias at 77K and 300K.
The device resistance $R_m$ calculated from the slope of the I-V plot (see Table 3-1), is the parallel combination of the resistances of the bridging wires ($R_i$) in the device, \textit{i.e.},

$$R_m = \frac{1}{\sum_{i=1,N} \frac{1}{R_i}}$$

(3-6)

where $N$ is the number of wires in the device.

The total resistance of an individual wire is the sum of bulk resistance $R_{bi}$ and contact resistance, $R_{ci}$ \textit{i.e.},

$$R_i = R_{bi} + R_{ci}.$$  

(3-7)

The bulk resistance of a wire is related to the bulk resistivity $\rho_b$ by,

$$R_{bi} = \rho_b \cdot \frac{l_i}{\pi r_i^2}.$$  

(3-8)

where $r_i$ and $l_i$ are the radius and length of wire $i$, respectively. The effective resistivity $\rho$ of a device is calculated from the measured resistances and the dimensions of the wires measured from SEM images using

$$\rho = R_m \cdot \sum_{i=1,N} \frac{\pi r_i^2}{l_i}.$$  

(3-9)

From (3-7) – (3-9),

$$\rho = \rho_b \cdot R_m \cdot \sum_{i=1,N} \frac{1}{R_i - R_{ci}}.$$  

(3-10)

So the effective resistivity calculated using (3-10) is equal to the bulk resistivity $\rho_b$ only in the absence of contact resistance ($R_{ci} \approx 0$) and greater otherwise.

**Resistance Model**

Bulk resistivity was calculated from the devices with the lowest resistivity and noise. As these devices have the lowest contact resistance, the resistivity calculated using
(3-10) and neglecting contact resistance gives the best estimate of the bulk resistivity. The carrier density $p$ is related to the bulk resistivity by the following expression;

$$\rho = \frac{1}{q\mu_p p}$$  \hspace{1cm} (3-11)

where $\mu_p$ is the hole mobility and $-q$ is the electron charge.

The corresponding carrier densities calculated using the resistivity versus impurity-concentration relationship for bulk Si at 300K [34], are $5 \times 10^{18}$ cm$^{-3}$ and $1.3 \times 10^{18}$ cm$^{-3}$ for wafers 1 and 2, respectively. Cui et al. [35] reported that the carrier mobility in highly doped silicon nanowires is comparable to that observed in bulk silicon. Consequently, the above listed values are assumed good estimates of the nanowire carrier densities. The bulk resistances of all other devices were calculated using these carrier concentrations. Note that dopant fluctuation is ignored in our analysis. This is a reasonable assumption given the large number of dopant atoms per wire. Also the physical diameters of the nanowire are used in the calculation. Due to the presence of surface charge, the surface region of the nanowire is expected to be depleted, and as a result the effective diameter becomes less than the physical diameter. The depletion width depends on the surface charge density and the number of traps filled. Our initial estimate of surface charge density is $2 \times 10^{12}$ q/cm$^2$. The calculation for the worst-case scenario shows that the resistance model presented here and the noise model (to be presented in chapter 5) remains valid. Since the surface charge density is not well characterized at this time, the analysis using the physical diameters of the nanowires is presented.
<table>
<thead>
<tr>
<th>Device</th>
<th>Number of wires</th>
<th>$R_m$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2</td>
<td>$1.76 \times 10^5$</td>
</tr>
<tr>
<td>b</td>
<td>2</td>
<td>$3.11 \times 10^5$</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>$1.38 \times 10^5$</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>$2.47 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wafer 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>2</td>
<td>$5.55 \times 10^4$</td>
</tr>
<tr>
<td>b</td>
<td>3</td>
<td>$4.85 \times 10^4$</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>$1.89 \times 10^5$</td>
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<td>d</td>
<td>5</td>
<td>$7.47 \times 10^4$</td>
</tr>
<tr>
<td>e</td>
<td>2</td>
<td>$5.08 \times 10^5$</td>
</tr>
<tr>
<td>f</td>
<td>1</td>
<td>$6.30 \times 10^5$</td>
</tr>
<tr>
<td>g</td>
<td>2</td>
<td>$1.76 \times 10^5$</td>
</tr>
<tr>
<td>h</td>
<td>2</td>
<td>$2.64 \times 10^5$</td>
</tr>
<tr>
<td>i</td>
<td>2</td>
<td>$3.93 \times 10^5$</td>
</tr>
</tbody>
</table>
From the devices containing only one nanowire, the contact resistance was obtained from
\[ R_c = R_m - R_b. \]  
(3-12)

It was observed that the contact resistance is inversely proportional to the cross-sectional area with a proportionality constant \( K_c \) of \( 1.69 \times 10^{-5} \, \Omega \cdot \text{cm}^2 \), i.e.,
\[ R_{ci} = \frac{K_c}{\pi r_i^2}. \]  
(3-13)

This model was applied to all other devices to calculate the contact resistance. The minimum and maximum contact resistances obtained from (3-13) for individual nanowires were 48.9 kΩ and 383 kΩ, respectively. The total resistance was calculated by combining the calculated contact and the bulk resistances. A plot of the measured resistance and the resistance calculated using the above model is shown in Fig. 3-8. The plot shows good agreement between the measured and the calculated resistance for all devices except for two devices.

Our model suggests a common mechanism for the contact resistance in all devices, most likely resulting from the interface between the impinging end of the nanowire and the sidewall. The base end of the nanowire is connected epitaxially to the silicon sidewall, and thus the contact resistance on this side should be negligible. On the impinging side however, the nanowire makes contact to the silicon electrode through the pinholes of the native oxide [36], so the contact resistance on this side is expected to be dominant. It is possible for the actual contact area to be different from the wire cross-section, because the nanowire has to burrow through a native oxide layer. However, the good fit of the model indicates that for all but two of the nanowires, the impinging
contacts are very uniform. A closer SEM examination of these two devices showed a nanowire with a contact area much smaller than the cross-section of the nanowire, which may explain why these two are different from the other devices. These two devices were not used for subsequent noise modeling.
Figure 3-8. Calculated vs. measured resistance, including contact resistance. The uncertainties in the calculated resistance due to the measurement uncertainties are shown. The uncertainties for the measured resistance are too small to be displayed in the plot. The devices having only one nanowire are marked with a circle.
CHAPTER 4
NOISE MEASUREMENTS

Noise Measurement System

A typical noise measurement system is shown in Fig. 4-1. The bias circuit shown is required to measure excess noise. The bias circuit needs to have lower noise than the device under test (DUT). Often the noise generated by the DUT is lower than the detectable range of the spectrum analyzer, for this reason the low noise amplifier (LNA) is used to amplify and bring the noise signal within the dynamic range of the spectrum analyzer. Brookdeal-5004, a commercially available LNA was used in this study. HP3561A, a low frequency spectrum analyzer (SA) was used to acquire the time domain data and calculate the voltage noise spectral density [37]. The computer workstation was used as an instrument controller for the SA and for importing the data for further processing.

Noise Characterization of the LNA

The noise characteristics of the LNA is of the highest importance as it is at the front of the signal chain [38]. For this reason the LNA was characterized for noise performance in the beginning of the study. The noise of the LNA can be adequately described in terms of a voltage and current noise source at the input node as shown in Fig. 4-2. If a resistor $R_s$ is connected to the input, the voltage noise spectral density measured at the output of the LNA is given by [38]

$$S_{vo} = A_{rej}^2 \cdot \left[4k_BT R_s + S_{in} R_s^2 + S_{in}\right]$$

(4-1)
Figure 4-1. Noise measurement setup.
where $A_{\text{eff}} = A_v \cdot R_i / (R_s + R_i)$, $R_i$, $S_{vn}$ and $S_{in}$ are the effective gain, input resistance, equivalent voltage and current noise sources of the LNA respectively. The current noise spectral density for the resistance $R_s$ is given by \[ S_{si} = 4k_B T / R_s. \] (4-2)

From (4-1) referring to the input side of the LNA;
\[ S_{vo} / A_{\text{eff}}^2 = 4k_B T R_s + S_{in} R_s^2 + S_{vn}. \] (4-3)

According to (4-3) a log-log plot of $S_{vo} / A_{\text{eff}}^2$ vs. $R_s$ should show three distinct regions (i) $S_{vo} / A_{\text{eff}}^2 = S_{vn}$, a constant for $S_{vn} \geq 4k_B T R_s \geq S_{in} R_s^2$ (ii) a slope ~1 region for $S_{vn} \leq 4k_B T R_s$ and $S_{in} R_s^2 \leq 4k_B T R_s$ and (iii) a slope ~2 region for $S_{in} R_s^2 \geq 4k_B T R_s \geq S_{vn}$.

One such plot is presented in Fig. 4-3. The plot indicates the different regions clearly however in region (iii) the effect of RC roll-off at higher frequency is visible. If the device resistance is within region (ii) a meaningful noise measurement can be made. If it is in region (i), the equivalent voltage noise of the LNA dominates and if in region (iii) the current noise of the LNA dominates. Regions (i) and (iii) are only visible at certain frequencies, this indicates that the equivalent noise sources are thus frequency dependent.

The extracted spectral densities $S_{vn}$ and $S_{in}$ using (4-3) are presented in appendix A.

**Instrument Control and Other Measurement Issues**

As mentioned in the previous section the LNA is used for amplification, as the noise signal is typically too small for the SA to detect directly. But a situation can arise when the noise signal is large enough to saturate the LNA and that will result in an incorrect noise reading.
Figure 4-2. Setup for the noise characterization of the low noise amplifier.
Figure 4-3: Voltage noise spectral density at the input side of Brookdeal-5004 LNA for different source resistance.
To prevent this situation, an analog oscilloscope was connected in parallel to the SA to monitor the output of the LNA for clipping during noise measurement. Also, even if the LNA does not saturate, a random high noise spike can overload the SA input during a noise measurement and again cause an incorrect reading. An instrument control routine was written in the HPVEE® graphical programming language to continuously check for an overload condition during measurement and stop the measurement if overload is detected. Additionally an option to select the attenuation level for the internal attenuator of the SA is added to the code that allowed precise control of the noise magnitude presented to the SA input. The SA collects a set of noise data for a certain time span, and then calculates the spectral noise density in the frequency domain. The calculated spectral noise density for the first 10% of the bandwidth is considered not accurate due to finite averaging time. So a control routine is written to start with the specified minimum frequency span and repeat the measurement for every decade of frequency range up to the maximum specified frequency and discarding the first 10% of the data for each decade. A flow chart of the instrument control program is presented in appendix B.

**Setup for Low Temperature Measurement**

The TO-8 package containing the device was placed in the sample chamber of a cryostat. The TO-package was mounted in a sample holder and placed on a copper finger to be cooled with liquid N₂. A layer of Iridium is placed between the TO-8 package and the sample holder to aid the conduction of heat. The connections to the pins of the TO-8 package are made through feed-throughs in the windows of the chamber using cryogenic wires and then the chamber is closed. The chamber is evacuated first using a mechanical
pump and followed by a rotary turbine pump in order to provide thermal isolation. A vacuum level of ~5mTorr was used for our experiments.

To cool the system, N$_2$ was placed in a pressurized container. N$_2$ liquid guided by the pressure travels through a heat exchanger that is thermally connected to the copper finger containing the sample. The N$_2$ flow rate is controlled by pressure applied to the N$_2$ container. The main temperature control is achieved by the flow rate and the heat transfer control in the heat exchanger. The lowest temperature achievable using this system is limited by the choice of N$_2$ as the coolant, which is approximately 77K.

To achieve a finer temperature control a feedback heating system consisting of a temperature sensor and a variable gain amplifier is used. The amplifier delivers a current to a resistive heater proportional to the difference of the temperature set by the user and the current temperature reading from the sensor. Using the amplifier gain for fine control a stable temperature level to ±0.1K within a few degrees of the desired temperature can be achieved easily.

**Overview of the Observed Noise Spectra**

The voltage noise spectral density $S_v$ was measured for frequencies between 10Hz and 100kHz and converted in to current noise spectral density $S_i$ using [39]

$$S_i = S_v / R^2$$

where $R$ is the resistance of the device under test (DUT). A typical plot of $S_i$ is given in Fig. 4-4. For both CNT and SNW devices the noise observed was a combination of excess noise and thermal noise. The current spectral density of the thermal noise is given by [37]

$$S_{thermal} = 4K_B T / R.$$
Figure 4-4. A typical plot of the measured current noise spectral density showing thermal noise and the $1/f$ noise and the Lorentzian components of the excess noise. The effect of RC roll off is visible at around 70 kHz.
CNTs reportedly exhibit shot noise but the full shot noise magnitude for the maximum bias level used in the study 13.9 µA, is $4.5 \times 10^{-24}$ A$^2$/Hz, below observed excess noise levels. Moreover the actual shot noise level is expected to be suppressed, placing it outside the range of observation [18]. The thermal noise level was higher ($6.624 \times 10^{-23}$ A$^2$/Hz for 1 kΩ resistor at 300K). The observed excess noise was mostly $1/f^\beta$ type noise [40]. The current noise spectral density for $1/f^\beta$ type of noise can be described by the following expression [39]:

$$S_{1/f} = \frac{A \cdot I^\alpha}{f^\beta}$$  \hspace{1cm} (4-6)

where $I$ is the dc current level, $f$ is the frequency, $A$, $\alpha$ and $\beta$ are constants expressing the relative noise magnitude, current and frequency exponent, respectively. The values of $A$ and $\beta$ are estimated by fitting a line to the experimental data as shown in Fig. 4-4. The parameter $\beta$ was found to be approximately equal to 1; hence this noise component is called $1/f$ noise.

The value of the current exponent $\alpha$ is equal to 2 for a device in linear mode as was the case for both CNT and SNW devices used in this study. An illustration of this relationship is shown in Fig. 4-5 for a CNT device. Note that at the lowest current level the $1/f$ noise is below the thermal noise floor at 1kHz, hence the plot for 1kHz deviates from slope 2. From this point on, $\alpha = 2$ is assumed and the following expression for $1/f$ noise will be used:

$$S_{1/f} = \frac{A \cdot I^2}{f^\beta}.$$ \hspace{1cm} (4-7)
Figure 4-5. Plot depicting the relationship between the 1/f noise and device current. The magnitude of 1/f noise is shown at different frequency points. The frequency spectra of the 1/f noise for the three current levels are shown in the inset.
For the CNT devices in some cases Lorentzian spectra were observed. These Lorentzian components arise when random number fluctuations are caused by processes with a single characteristic time and activation energy. A Lorentzian component can be characterized as [13],

\[ S_L(f) = \frac{S_L(0)}{1 + \omega^2 \tau^2} \]  

(4-8)

where \( S_L(0) \) is the plateau value of the Lorentzian, \( \omega \) is the angular frequency and \( \tau \) is a characteristic time. No Lorentzian component was observed in the SNW devices. The result and analysis of the 1/f and Lorentzian components will be discussed in details in subsequent chapters.
CHAPTER 5
NOISE IN SILICON NANOWIRES

Introduction

The result of the resistance measurement for these devices was presented in chapter 3. The measured resistivity and the 1/f noise coefficient $A$ presented in Table 5-1 show significant variations from device to device. However the plot of $A$ vs. $\rho$ (Fig. 5-1) shows that the devices from both wafers that have the lowest effective resistivity also generally show the lowest noise. Based on discussions in chapter 3, these devices can be identified as the devices with low contact resistance. The fact that the low-noise devices also have low contact resistance suggests that the source of the noise is the contact. To check this possibility further a noise model was developed and will be presented next.

Noise Model

The proposed noise model includes bulk contact components just like the bulk and contact components of resistance. The circuit diagram of the model is shown in figure 5-2. From this circuit, the measured open-circuited noise voltage across the terminals is given by

$$v_n = i_{bn} \cdot R_h + i_{cn} \cdot R_c$$  \hspace{1cm} (5-1)

where $i_{bn}$ and $R_h$ are the noise current source and the resistance respectively for the bulk region, and $i_{cn}$ and $R_c$ are the noise current source and the resistance respectively for the contact region of a wire.
Figure 5-1. $1/f$ noise coefficient $A$ vs. effective resistivity $\rho$. The uncertainties in $A$ and $\rho$ due to the measurement uncertainties are shown.
## TABLE 5-1 Relative noise magnitude

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of wires</th>
<th>( A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>2</td>
<td>( 6.71 \times 10^{-9} )</td>
</tr>
<tr>
<td>b</td>
<td>2</td>
<td>( 1.20 \times 10^{-9} )</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>( 2.92 \times 10^{-11} )</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>( 8.45 \times 10^{-9} )</td>
</tr>
<tr>
<td>Wafer 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>2</td>
<td>( 1.22 \times 10^{-9} )</td>
</tr>
<tr>
<td>b</td>
<td>3</td>
<td>( 3.37 \times 10^{-10} )</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>( 1.61 \times 10^{-10} )</td>
</tr>
<tr>
<td>d</td>
<td>5</td>
<td>( 4.04 \times 10^{-11} )</td>
</tr>
<tr>
<td>e</td>
<td>2</td>
<td>( 1.69 \times 10^{-10} )</td>
</tr>
<tr>
<td>f</td>
<td>1</td>
<td>( 2.76 \times 10^{-10} )</td>
</tr>
<tr>
<td>g</td>
<td>2</td>
<td>( 3.51 \times 10^{-11} )</td>
</tr>
<tr>
<td>h</td>
<td>2</td>
<td>( 4.21 \times 10^{-11} )</td>
</tr>
<tr>
<td>i</td>
<td>2</td>
<td>( 4.73 \times 10^{-10} )</td>
</tr>
</tbody>
</table>
Figure 5-2. Circuit representation of the noise model
From (5-1) the total 1/f voltage noise spectral density $S_v$ in terms of the individual current noise spectral densities is given by

$$S_v = S_{ib} \cdot R_b^2 + S_{ic} \cdot R_c^2$$  \hspace{1cm} (5-2)$$

where $S_{ib}$ and $S_{ic}$ are the current noise densities of the bulk and contact noise sources, respectively.

From (5-2), with the total resistance,

$$R = R_b + R_c,$$  \hspace{1cm} (5-3)$$

the total current noise spectral density can be written as,

$$S_i = S_{ib} \cdot \left(\frac{R_b}{R}\right)^2 + S_{ic} \cdot \left(\frac{R_c}{R}\right)^2.$$  \hspace{1cm} (5-4)$$

Using (4-7), the expression for 1/f noise with $\beta \approx 1$,

$$S_i = \frac{A}{f} \cdot I_{dc}^2 = \frac{A_b}{f} \cdot I_{dc}^2 \cdot \left(\frac{R_b}{R}\right)^2 + \frac{A_c}{f} \cdot I_{dc}^2 \cdot \left(\frac{R_c}{R}\right)^2$$  \hspace{1cm} (5-5)$$

where $A_b$ and $A_c$ are the 1/f noise coefficients for the bulk and the contact region, respectively. Equation (5-5) can be simplified to

$$A = A_b \cdot \left(\frac{R_b}{R}\right)^2 + A_c \cdot \left(\frac{R_c}{R}\right)^2.$$  \hspace{1cm} (5-6)$$

Most of the devices studied contained multiple nanowires. For those cases, the total noise of the device is the sum of the noise contribution from all the nanowires in the device. From (4-7)

$$S_i = \frac{A}{f} \cdot I_{i}^2 = \sum_{i=1}^{N} \frac{A_i}{f} \cdot I_{i}^2$$  \hspace{1cm} (5-7)$$

$$\Rightarrow A_i = \sum_{i=1}^{N} \frac{I_{i}^2}{I_{i}^2}$$  \hspace{1cm} (5-8)$$
where $A_i$ and $I_i$ are the combined noise coefficient and current for all the nanowires in the
device under study and, $A_i$ and $I_i$ are the noise coefficient and current for the $i$-th
nanowire. Using (5-6) - (5-8)

$$A_i = \sum_{i=1}^{N} \left[ A_{bi} \cdot \left( \frac{R_{bi}}{R_i} \right)^2 + A_{ci} \cdot \left( \frac{R_{ci}}{R_i} \right)^2 \right] \cdot \left( \frac{I_i}{I_t} \right)^2. \quad (5-9)$$

From (5-9), the bulk and contact noise components can be separated. The bulk
noise is given by

$$A_b = \sum_{i=1}^{N} \left[ A_{bi} \cdot \left( \frac{R_{bi}}{R_i} \right)^2 \right] \cdot \left( \frac{I_i}{I_t} \right)^2 \quad (5-10)$$

and the noise component from the contact is given by,

$$A_c = \sum_{i=1}^{N} \left[ A_{ci} \cdot \left( \frac{R_{ci}}{R_i} \right)^2 \right] \cdot \left( \frac{I_i}{I_t} \right)^2, \quad (5-11)$$

with \[ A_i = A_b + A_c. \quad (5-12) \]

If either $A_b$ or $A_c$ is known, the other one can be calculated from (5-12).

The noise component of the bulk can be accurately determined from the devices
that have negligible contact resistance. To understand this consider (5-9). For negligible
contact resistance, \textit{i.e.} $R_b \gg R_c$, we have $R \approx R_b$ and $R \gg R_c$. Then from (5-9)

$$A \approx A_b. \quad (5-13)$$

Also, from (5-10) with $R_i \approx R_b$,

$$A_b = \sum_{i=1}^{N} \left[ A_{bi} \right] \cdot \left( \frac{I_i}{I_t} \right)^2. \quad (5-14)$$

From the well known Hooge model for bulk 1/f noise [39],
\[ A_{bi} = \frac{\alpha_{Hb}}{p \cdot V_i} \]  

where \( \alpha_{Hb} \) is the Hooge parameter, \( p \) is the density of carriers and \( V_i \) is the volume of the \( i \)-th wire. Using the Hooge model in (5-14),

\[ A_b = \alpha_{Hb} \cdot \sum_{i=1}^{N} \frac{1}{p \cdot V_i} \left( \frac{I_i}{I} \right)^2 \]  

\[ \Rightarrow \alpha_{Hb} = \frac{A_b}{\sum_{i=1}^{N} \frac{1}{p \cdot V_i} \left( \frac{I_i}{I} \right)^2}. \]  

The Hooge parameters were calculated from the devices with the lowest resistivity and noise. As these devices have the lowest contact resistance, the \( \alpha_{Hb} \) calculated using (5-17) gives the best estimate of the bulk Hooge parameter. The calculated Hooge parameters are \( 1.1 \times 10^{-5} \) and \( 7.5 \times 10^{-6} \) for wafer 1 and wafer 2, respectively. In general the value of the Hooge parameter is a good indicator of the process quality, and the values obtained for the Si nanowires are comparable to Hooge parameters for modern low noise silicon bulk devices [40]. Using these calculated Hooge parameters the bulk and contact noise \( A \) values for the other devices were calculated using (5-10), (5-11) and (5-16).

However, unlike bulk noise, there is no known model for contact noise, so the contact noise magnitude per wire \( (A_{ci}) \) cannot be calculated directly from (5-11). To calculate the contact noise it is necessary to assume a functional dependence between the noise magnitude and some physical parameter such as the radius or length. One can expect the contact noise to be some function of radius but independent of length. Hence, the following model for the contact noise was adopted,

\[ A_{ci} \propto r_i^m \]  

(5-18)
where \( r_i \) is the radius of the nanowire. The exponent \( m \) determines how the noise is related to the physical parameter of the corresponding nanowire. For example, for \( m = 0, 1 \) and 2, the noise is independent, proportional to the radius and proportional to the cross-sectional area respectively. The values for \( m \) tested for a fit were \(-3, -2, -1, 0, 1, 2 \) and \( 3 \). The best fit to the data was obtained for \( m = -2 \), in other words the best-fit model suggests the relative noise is inversely proportional to the cross-sectional area of the nanowire \( i.e., \)

\[
A_{ci} \propto \frac{1}{\pi r_i^2} . \tag{5-19}
\]

The proportionality constants for wafers 1 and 2 are \( 4.7 \times 10^{-18} \) cm\(^2\) and \( 4.6 \times 10^{-19} \) cm\(^2\), respectively. It was shown in chapter 3 that the contact resistance is also inversely proportional to the contact area. Comparing (3-13) and (5-19);

\[
A_{ci} \propto R_{ci} . \tag{5-20}
\]

This model suggests that the contact noise is proportional to the contact resistance, which is reasonable, considering that both the noise and the resistance indicate the quality of the contact. The calculated contact noise from measurements and the modeled noise are shown in Fig. 5-4. The plot shows good agreement between the model and the measured noise and also shows that the agreement is worse if the magnitudes of the bulk and contact noise components become comparable. This is expected because the calculation involves subtracting two statistical quantities; consequently, when the magnitudes of the two noise components are comparable, the error in \( A_c \) calculated using (5-12) would become higher.
Figure 5-4. Contact and bulk noise components calculated from measured data. The contact noise component calculated from the model is also shown. The calculated uncertainties due to measurement uncertainties are indicated.
Summary and Conclusion

The resistance model presented enables the calculation of the bulk and contact components of the resistance. The contact resistance is believed to originate from the impinging end of the nanowire where the nanowire connects to the uncatalyzed silicon layer. To estimate the relative magnitudes of the bulk- and contact-resistance components, consider a typical nanowire with a length and radius of 8µm and 50nm, respectively. For a doping level of $1 \times 10^{18}/\text{cm}^3$, the bulk resistance is 424 kΩ. The contact resistance calculated from the model is 215 kΩ, and is a significant portion of the total resistance, which, may be reduced by improved processing. The bulk 1/f noise coefficient for this nanowire for a Hooge parameter of $1 \times 10^{-5}$ is $5 \times 10^{-10}$. The 1/f noise coefficient for the contact noise from the model is $1 \times 10^{-8}$, for a proportionality constant of $1 \times 10^{-19}$. Hence the contact noise is the dominant noise mechanism in this nanowire. The likely mechanism for noise in the case of our devices is carrier trapping-detrapping in defects producing the well-known 1/f-like number fluctuation noise spectra [37]. The impinging end of the wire, where contact to the silicon electrode is made through possibly pinholes in the native oxide, is expected to be defect rich and thus the dominant source of contact noise whereas the base end of the nanowire is connected epitaxially to the silicon sidewall creating a defect lean, lower noise contact configuration. Furthermore, because of the higher resistance on the impinging side, any fluctuations in this contact will couple out more to the device contacts.

This analysis shows that the Hooge parameter for SNWs, the figure of merit for bulk noise performance, is within the range of Hooge parameters for modern low noise bulk devices [40]. Because the contact was identified as the dominant source of noise,
further noise reduction can envisioned by optimizing the contact. Reducing the contact resistance can potentially reduce contact noise because they originate from a common mechanism, as indicated by (5-20); moreover less contact noise will couple out into the remainder of the circuitry as the contact resistance becomes a smaller fraction of the total resistance.
CHAPTER 6
SEQUENTIAL ABLATION OF CARBON NANOTUBES

During the CNT growth process typically multiple CNTs grow and bridge the gap between the metallic contacts. Due to the random nature of the CNT growth of the total number of these CNTs two thirds are expected to be semiconducting and the rest metallic tubes [41]. In order to study a single CNT, a single CNT needs to be identified. Commonly that is done using an Atomic Force Microscope (AFM). Once a CNT is located and marked, the contacts can be placed and electrical measurements made. Alternatively, CNTs are grown on a wafer containing a matrix of contacts. It is then necessary to find a single CNT connecting two contacts with the help of AFM for this case as well. Both of these processes are very time consuming and limit the number of CNTs that can be studied. In our experiments due to the large size of the contacts, multiple metallic and semiconducting CNTs are contacted simultaneously and a pulsed voltage bias tube ablation method was implemented to delineate the noise and charge transport properties of the metallic and semiconductor tubes [42-43]. Although destructive, this method is suitable for extracting and comparing the noise properties of the metallic and semiconducting CNTs because it allows the measurement of multiple CNTs in a short period of time and due to the close proximity of the measured CNTs the process variation is kept to a minimum.

Setup for the Sequential Ablation Technique

The samples were placed at room temperature in a pulsed bias circuit that allowed for approximately 10µs duration voltage bias pulses applied at the drain terminal at a
repetition rate of 80Hz as depicted in Fig. 6-1. A positive, continues gate bias of +14V was applied so that only the metallic tubes contribute to conduction. Upon slowly increasing the level of the pulsed bias voltage at the drain and monitoring the device current on an analog oscilloscope, the onset of Joule heating in a metallic tube could be observed from small fluctuations in the current. Upon further increase of the pulsed drain bias, a tube was ablated and the pulsed bias was switched quickly to the 1kΩ dissipative resistor preventing damage to additional tubes. The ablation occurred approximate at +17V for a pulse width of 6µsec and a repetition rate of 80Hz. Current-voltage and noise measurements were carried out before and after the ablation of each tube using a HP4351 semiconductor parameter analyzer and a HP3561A low frequency spectrum analyzer operating between 10Hz and 100KHz. As mentioned in chapter 4, the noise observed is a combination of low frequency 1/f-like excess noise and thermal noise. Shot noise levels were below the detection range of our experiment.

**Result and Analysis**

The conductances of the metallic and the semiconducting CNTs were extracted from the measured current-voltage characteristics. At sufficiently high gate voltage $V_g$, in this case +14V or higher, the semiconducting CNTs are turned off, as a result the measured conductance, $G_m$ represents the total parallel conductance of the metallic CNTs. The semiconducting CNTs are turned ON at $V_g = -14V$. So at this gate voltage the measured conductance $G_t$ represents the conductance of all the CNTs including the metallic and semiconducting CNTs. Now the total parallel conductance of the semiconducting CNTs, $G_s$ is obtained using,

$$G_s = G_t - G_m$$  \hspace{1cm} (6-1)
Figure 6-1. Pulsed bias experimental set-up for sequential ablation of metallic CNTs.
The low bias conductance of metallic and semiconducting CNTs in sample A measured after an ablation event, are plotted as a function of the number of tube ablations in Fig. 6-2. The plot clearly shows the conductance change of the metallic CNT matrix due to ablation, while the total conductance of the semiconducting tube matrix remains unchanged as expected. As metallic tubes are ablated successively, the total number of CNTs remaining becomes less and as a result the total conductance drops, which is confirmed by the measured data shown in Fig. 6-2, except after the first ablation attempt. The increase in conductance after the first ablation attempt appears to be the result of an annealing effect, which will be discussed later in the next section. From the difference in measured conductance before and after an ablation the conductance of the ablated CNT is obtained. The calculated conductances of the ablated CNTs are presented in Fig. 6-3. From the data the average conductance of a single metallic tube is calculated to be $2.7 \times 10^{-5}$ S or 37 kΩ. No metallic or semiconducting CNTs were found to be connecting after the 7th ablation attempt; the most probable cause is static damage during the measurements. However, the total number of metallic CNTs in the sample can be estimated from extrapolating the fitted line in Fig. 6-2. It was estimated that the original sample contained 8 metallic tubes. Under random CNT growth conditions typically 1/3 of the tubes show metallic properties while 2/3 becomes a p-type semiconductor for the Pd contact system used in this experiment [41]. Consequently sample A is expected to have contained 16 semiconductor tubes for a total of 24 tubes originally.

By measuring the linear conductance of the samples at $V_g = -14$ V (semiconductor and metallic tubes both conducting) and at $V_g = +14$ V (metallic tubes only) the conductance of the semiconductor tubes at $V_g = -14$ V can now be estimated.
Figure 6-2. The measured low bias conductances of metallic and semiconducting CNTs in sample A, plotted as a function of the number of CNT ablation attempts performed on the sample.
For sample A, this resulted in 1.7 MΩ per semiconductor tube. The spread in data displayed in Fig. 6-3 is in line with values reported in the literature and may be due to small variations in the Pd metal contact-CNT interfaces from sample to sample [44].

From (4-7) the measured 1/f noise of carbon nanotubes can be expressed as

$$S_i(f) = \frac{A_i \cdot I_i^2}{f^\beta}$$

(6-2)

where the excess noise factor $A_i$ models the relative magnitude of the excess noise and $\beta$ is the frequency exponent. The value of $A_i/R_t$, where $R_t$ is the total ohmic resistance of the sample, has been shown to be close to $10^{11} \, \Omega^{-1}$ for single CNTs [7]. Assuming that the parallel CNTs in our samples produce noise independently, the total 1/f noise can be formulated as a combination of noise contributions from the metallic and semiconducting CNTs;

$$S_i(f) = \frac{A_i \cdot I_i^2}{f^\beta} = \sum_{i=1}^{M} \frac{A_{mi} \cdot I_{mi}^2}{f^\beta} + \sum_{j=1}^{S} \frac{A_{sj} \cdot I_{sj}^2}{f^\beta}$$

(6-3)

where the subscript $m$ and $s$ denotes the metallic and semiconducting noise and current contributions, and, $i$ and $j$ subscripts represent the individual metallic and semiconducting CNTs respectively. $M$ and $S$ are the total number of metallic and semiconducting CNTs in the sample. Simplifying (6-3),

$$A_i = \sum_{i=1}^{M} A_{mi} \cdot \left( \frac{I_{mi}}{I_i} \right)^2 + \sum_{j=1}^{S} A_{sj} \cdot \left( \frac{I_{sj}}{I_i} \right)^2$$

(6-4)

Writing in terms of the total and individual metallic and semiconducting CNT conductances,

$$A_i = \sum_{i=1}^{M} A_{mi} \cdot \left( \frac{G_{mi}}{G_i} \right)^2 + \sum_{j=1}^{S} A_{sj} \cdot \left( \frac{G_{sj}}{G_i} \right)^2$$

(6-5)
Figure 6-3. Calculated conductances of the ablated metallic CNTs for sample A.
where $G_{mi}$ and $G_{sj}$ subscripts represent the conductance of the individual metallic and semiconducting CNTs respectively. And $G_t$ represents the total conductance of the device. From (6-5)

$$A_i \cdot G_i^2 = \sum_{i=1}^{M} A_{mi} \cdot G_{mi}^2 + \sum_{j=1}^{S} A_{sj} \cdot G_{sj}^2.$$  \hfill (6-6)

From (6-6) it is evident that the noise measurements at $V_g = +14V$ represents the 1/f noise contributions for the metallic CNTs. Because at this gate bias, the semiconductor tubes are cut-off, $G_S \approx 0$, and presumably contribute negligible noise levels. This assumption was validated by the result of the analysis as it will be shown later in this section.

From (6-6) it also follows that at each successive ablation of a CNT the measured $A_i \cdot G_i^2$ will decrease. The change in $A_i \cdot G_i^2$ represents the lost noise contribution (and conductance) from the ablated CNT. This successive drop in the measured $A_i \cdot G_i^2$ value is illustrated in Fig. 6-4 for $V_g = +14V$ where the second term on the right hand side of (6-6) has a negligible contribution. The conductance of the ablated CNTs is known from the current-voltage measurements, so the 1/f noise coefficient of the ablated CNT can be obtained from (6-6). For sample A, the calculated values for $A_m$ and $A_m/R_m$ are presented in Fig. 6-5. The average value of $A_m$ for sample A was found to be $2 \times 10^{-5}$ resulting in $\langle A_m/R_m \rangle = 4.9 \times 10^{-10} \text{S}$. Note that the measurement data after the very first ablation was not used to calculate the average because of the observed annealing effect, to be discussed in detail later. Analyzing the noise data measured at $V_g = -14V$ which includes semiconductor and metallic tube noise contributions resulted in $\langle A_s \rangle = 3.7 \times 10^{-3}$ or $\langle A_s/R_s \rangle = 2.2 \times 10^{-9} \text{S}$. 
Figure 6-4. Measured $A/r_{t}$ and $A_t G_t^2$ at $V_g = +14V$ for sample A, plotted as a function of the number of CNT ablation attempts performed on the sample.
Figure 6-5. Calculated $A$ and $A/R$ for the ablated metallic CNTs for sample A.
Measurements were performed on sample B on the same wafer and on sample C on a different wafer. For both of the samples B and C, complete ablation of the metallic CNTs was achieved, so only semiconducting CNTs remained at the end of the experiment. A summary of the data is presented in Table 6-1 and the \( A \) vs. \( R \) plot for all the data points collected is presented in Fig. 6-6. The values of the frequency noise exponent \( \beta \) range between 0.8 and 1.2 for the samples studied.

The measured \( A/R \) values almost all exceed the average \( 9 \times 10^{-11} \Omega^{-1} \) value reported by Snow et al. [8]. From this we conclude that our samples are relatively noisy which may be attributed to the sputtering deposition of the Pd contacts. Also it is clear that in contrast to conventional metal and semiconductor systems where the excess noise of metals can be typically ignored, the excess noise of metallic tubes needs to be accounted for. Also note that the extracted \( A \) values validate our initial assumptions made in the analysis of the data.

**Details of the Observed Annealing Effect**

As mentioned before, an annealing effect was observed in our experiment. The first time a sample was subjected to the pulsed bias, the conductance of the sample increased while the noise level improved. The conductance improvement at the first ablation attempt is obvious from Fig. 6-2. The effect of the 1/f noise level improvement can be seen in Fig. 6-4. Note that \( A_i \cdot G_i^2 \) decreases after the first ablation attempt even though the conductance \( G_i \) increases, which suggests a reduction in the 1/f noise coefficient \( A_i \). Furthermore the difference between the measured noise level before and after the first metallic CNT ablation was found to be roughly 2 to 4 times higher than the rest. This again suggests an improvement of noise during the first ablation attempt.
Figure 6-6. Calculated $A$ vs. $R$ values for the ablated CNTs. The solid and open symbols represent the metallic and semiconducting CNTs respectively. The data points estimated from the remaining semiconducting CNTs after all the metallic CNTs have been ablated are indicated with a circle.
So it appears that during the application of power to a virgin CNT sample an annealing effect is occurring due to Joule heating. This also raises the question whether the results for the individual CNTs presented are valid as the ablation process itself may change the property of the CNT being measured. To answer this question we turn our attention to the $A_t/R_t$ plot shown in Fig. 6-4. The parameter $A_t/R_t$ can be considered as a figure of merit for the comparison of relative noise magnitudes of CNT samples [7]. The noise reduction at the first ablation attempt due to annealing is clearly visible from the large change in the $A_t/R_t$ plot. However after the very first ablation attempt the change in the $A_t/R_t$ values lies within the statistical spread of our data and would not affect the result appreciably.

Furthermore, the calculated parameters for the individual ablated CNT’s conductances (see Fig. 6-3) and noise magnitudes (see Fig. 6-5) also do not show an appreciable trend over successive ablations. So we conclude that the ablation process does not change the properties of the CNTs appreciably after the initial ablation.

**Summary and Conclusions**

The pulsed bias experiments were successful in demonstrating the sequential ablation of single metallic carbon nanotubes. The conductance and relative excess noise factors of semiconductor and metallic tubes were determined showing that both produce $1/f$ like excess noise. However the relative $1/f$ noise level in the metallic tubes as expressed by the parameter $A$ is two orders of magnitude lower, and the ratio $A/R$ is between a factor 3 to three orders of magnitude lower than in the semiconducting CNTs. There is a large spread in the resistance of both metallic and semiconducting CNTs in all three samples measured (see Table 6-1). However both $A$ and the factor $A/R$, used as a figure of merit for noise comparison is consistently higher for semiconducting CNTs in all cases. In two instances during ablation attempts on sample B and C, it was observed
that semiconducting CNTs were ablated along with metallic CNTs. The most likely reason for this is static damage caused by connecting the devices to the measurement equipment as mentioned earlier. This unintended ablation of semiconducting CNTs provided an opportunity to measure the resistance and the noise contribution of the ablated CNT directly, rather than calculating the resistance and noise contribution from the remaining semiconducting CNTs after all the metallic CNTs were ablated. The resistance and the noise contribution for these semiconducting CNTs were found to be within the same range as the semiconducting CNTs remained after metallic CNTs were ablated.

Sample C was from a different wafer than sample A and B. Sample C was annealed in Ar at 220°C for 10 minutes, while sample A and B were not annealed. The resistance of the metallic CNTs in sample C is higher compared to the samples A and B. However it is possible that this higher resistance is not caused by annealing but simply results from process variations from wafer to wafer. Furthermore, the resistance of the semiconducting CNTs for sample C is within the range of resistances of the semiconducting CNTs in sample A and B. The 1/f noise level in sample C does not show an appreciable change from the other two samples. Hence the thermal annealing process used did not have an effect on the noise properties of CNTs.

The fact that the annealing caused by the Joule heating due to current flow in the device improves the conductance and lowers the 1/f noise level points to the contact as the dominant source of 1/f noise. Because the CNT operates as a one-dimensional conductor, most of the power is dissipated in the contact region [45], and an improvement of the quality of the contact between the CNT and Pd caused by the Joule heating is
evident from the lowering of the contact resistance. Similarly, the improvement in the noise level can be attributed to annealing out defects in the contact area. An annealed contact is likely to have a lower number defect related traps, hence results in a lower noise level.
Table 6-1 Noise and conductance data of samples A, B and C.

<table>
<thead>
<tr>
<th>Device Data</th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Metallic Tubes</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Estimated Number of Semiconducting CNTs</td>
<td>16</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Estimated Total Number of CNTs</td>
<td>24</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>(\langle R_m \rangle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>37kΩ</td>
<td>103kΩ</td>
<td>4.6MΩ</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>12kΩ</td>
<td>44kΩ</td>
<td>-</td>
</tr>
<tr>
<td>(\langle R_s \rangle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1.7MΩ</td>
<td>189kΩ</td>
<td>498kΩ</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>-</td>
<td>180kΩ</td>
<td>398kΩ</td>
</tr>
<tr>
<td>(\langle A_m \rangle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>2.0×10^-5</td>
<td>1.9×10^-5</td>
<td>1.1×10^-4</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>1.9×10^-5</td>
<td>1.3×10^-6</td>
<td>-</td>
</tr>
<tr>
<td>(\langle A_m/R_m \rangle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>4.9×10^-10S</td>
<td>2.0×10^-10S</td>
<td>2.3×10^-11S</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>3.1×10^-10S</td>
<td>7.4×10^-11S</td>
<td>-</td>
</tr>
<tr>
<td>(\langle A_s \rangle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3.7×10^-3</td>
<td>3.8×10^-3</td>
<td>2.7×10^-2</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>-</td>
<td>5.5×10^-3</td>
<td>1.3×10^-2</td>
</tr>
<tr>
<td>(\langle A_s/R_s \rangle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>2.2×10^-9S</td>
<td>1.4×10^-8S</td>
<td>1.2×10^-7S</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>-</td>
<td>1.1×10^-8S</td>
<td>1.3×10^-7S</td>
</tr>
</tbody>
</table>
CHAPTER 7
LORENTZIAN TYPE OF NOISE IN CARBON NANOTUBES

Introduction to the Lorentzian Noise Component

An overview of the noise properties of CNT devices was presented in chapter 4. In Fig. 4-4 a measured plot of the current noise spectral density ($S_i$) was given. A closer examination of this plot reveals the presence of Lorentzian noise components superimposed on the $1/f$ like noise. The presence of a Lorentzian component becomes clear when the fitted $1/f$ like noise is subtracted from the measured excess noise as shown in Fig. 7-1.

Lorentzian components arise when random number fluctuations are caused by processes with a single characteristic time and activation energy. A Lorentzian component can be characterized as

$$S_L(\omega) = S_L(0) \frac{1}{1 + \omega^2 \tau^2} \quad (7-1)$$

where $S_L(0)$ is the plateau value of the Lorentzian, $\omega$ is the angular frequency and $\tau$ is a characteristic time. The plateau values and the characteristic times can be obtained from fitting the curve given by equation (7-1) to the data. The fitted curve is shown as a dotted line in Fig. (7-1).

The Lorentzian(s) that showed up at a particular temperature shifts to down vertically and to a higher frequency as shown in Fig. 7-2. This movement of a particular Lorentzian over temperature can be tracked until it moves out of the frequency range of measurement.
Figure 7-1. Extraction of Lorentzian spectra from excess noise; (a) a typical excess noise plot (top) with fitted 1/f noise line, and (b) bottom plot shows the Lorentzian spectra obtained after subtracting 1/f noise from the excess noise.
Figure 7-2. A diagram describing the shift of Lorentzian spectra with temperature.
Results and Analysis

The noise measurement was repeated over a temperature range of 77K to 300K on two devices (A and B). Several Lorentzians were observed and tracked across this temperature range and their corresponding characteristic times ($\tau$) were extracted. The calculated values for $\tau$ at different temperature are shown in Fig. 7-3 for devices A and B, respectively. Note that the horizontal axis is 1000/T, where T is temperature in Kelvin. From the plot, it is evident that the characteristic times $\tau$ increase with decreasing temperature and are clearly thermally activated i.e.,

$$\tau = \tau_0 \cdot \exp\left(\frac{E}{k_B T}\right),$$

(7-2)

where $E$ is the activation energy and $k_B$ is the Boltzmann constant. This equation is well known to explain the characteristic times of thermally activated generation-recombination noise components in semiconductors with $E = E_T - E_F$, where $E_T$ is the trap or defect energy level to which the carrier is activated and $E_F$ is the Fermi level [13]. The activation energies calculated from the plot shown in Fig. 7-3 are listed in table 7-1. The position of $E_F$ in the semiconducting carbon nanotubes is determined by the work-function difference of the Pd/CNT contact system placing $E_F$ in these devices near the valence band edge, independent of temperature [44]. As a result the values listed in table 7-1 can be interpreted as hole activation energies for carrier detrapping from different defect or trap centers.

Figure 7-3 also shows that at sufficiently low temperatures the characteristic times tend to reach a constant value. This trend is expected and originates from the mechanism of the carrier trapping and detrapping process itself.
Figure 7-3. Lorentzian characteristic times for device A and B shown in solid and dashed lines respectively. For sample A, the activation energies of the Lorentzians are 0.31, 0.27, 0.21 and 0.08 eV for Lorentzians I-A, II-A, III-A and IV-A, respectively. For sample B, the activation energies are 0.42, 0.51, 0.2 and 0.29 eV for Lorentzians I-B, II-B, III-B and IV-B, respectively.
The measured characteristic time $\tau$ is the reciprocal sum of the carrier capture time $\tau_c$ and the emission time $\tau_e$, i.e.,

$$\frac{1}{\tau} = \frac{1}{\tau_c} + \frac{1}{\tau_e}. \quad (7-3)$$

$\tau_e$ is a strong function of temperature because the energy available to the trapped carrier is a function of temperature. At a higher temperature, it is easier for the trapped carrier to acquire the energy required to come out of the trap and as a result, the time a carrier spends in the trap on average decreases, hence $\tau_e$ is lower at higher temperatures.

Conversely, $\tau_c$ is relatively independent of temperature [39] because the trapping process is a random process dependent on the capture cross-section of the trap and trap availability. At higher temperature, $\tau_c << \tau_e$, hence $\tau_e$ dominates the observed value of $\tau$.

At lower temperature $\tau_e >> \tau_c$, so $\tau_c$ dominates and $\tau$ becomes independent of temperature.

From data it was observed that the plateau values of the Lorentzians $S_L(0)$, have a linear relationship with $\tau$ that can be described as

$$S_L(0) = \chi \cdot \tau. \quad (7-4)$$

For device A, the value for $\chi$ was found to be $3.1 \times 10^{-17}$. For device B, the noise measurement at each temperature was performed at the gate voltage levels of $V_g = 0$ and $+14V$. In Fig. 7-4, a plot of the $S_L(0)$ vs. $\tau$ measured at different temperatures is presented. From the plot it is apparent that the linear relationship described in (7-4) is also valid here. For this case the estimated values for $\chi$ are $3.8 \times 10^{-17}$ and $4.7 \times 10^{-17}$ for $V_g = 0$ and $+14V$ respectively. This linear relationship suggests that the variance of the number of carriers $\langle \Delta N^2 \rangle$ is a constant [13].
Table 7-1 Activation energies calculated using equation (7-2).

<table>
<thead>
<tr>
<th>Activation energies in eV</th>
<th>Device A</th>
<th>Device B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.08</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>0.27</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>0.31</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Figure 7-4. A plot of the Lorentzian Plateau value vs. characteristic time for device B at $V_g = 0$ and 14V. The linearly fitted data is also shown.
Figure 7-5. A plot of the Lorentzian Plateau value and characteristic time at different gate voltages for device A.
Effect of Gate Voltage

Figure 7-4 and the results discussed above also suggest that the gate voltage does not change the Lorentzians appreciably. To verify this observation, sample B was measured at different gate voltages at room temperature (approximately 300K). The results of these measurements shown in Fig. 7-5, do not show a clear dependence on gate voltage; thus confirming our previous observation. This observation is important and may help pin point the physical location of the noise generating trap center.

First note that the Lorentzians are visible from $V_g = -14V$ to $+14V$. In a conventional device Lorentzians are associated with semiconducting materials, since in a metallic system, because of the presence of a large number of carriers, an individual trap center does not produce a noticeable effect on the transport characteristics. However, in this case the Lorentzian is clearly associated with a metallic CNT as at $V_g = +14V$, where a semiconducting CNT would not conduct and hence an associated Lorentzian will not show up.

The calculated activation energies for the noise components are within the range of energies of physical processes possibly present in the carbon nanotubes studied. For example, the fluctuations caused by carrier transitions between one-dimensional sub-bands will have activation energies equal to the energy difference between sub-bands. The sub-band energy differences in carbon nanotubes can be close to the discrete activation energies presented in table 7-1. Also, it may be possible that the noise originates from local defect centers due to adsorption of a chemical species. It has been reported that oxygen chemisorption on the surface of a semiconducting carbon nanotube lowers the energy band gap. For example on a (8,0) SWNT the energy gap decreased
from 0.56eV to 0.23eV due to oxidation [46]. Local defects of this nature may produce
noise with activation energies in the range reported in this work.

However, the gate voltage insensitivity suggests that the defects associated with the
Lorentzians are located at or very close to the contact region of the CNT device since the
band bending due to the gate voltage is minimum near the contact region of a
semiconducting CNTs. As shown in Fig. 3-4 the energy band bends due to the application
of gate voltage and as a result the quantity \( E (= E_T - E_F) \) described in equation (7-2) will
change. The change in \( E \) is not uniform across the device. It has a maximum at the center
of the device and a minimum near the contacts. For a large change in gate voltage one
would expect a significant change in \( E \) and a noticeable change in \( \tau \) via equation (7-2). In
the absence of any such effect on \( \tau \), we postulate that the defects that generate the
observed Lorentzians are not located at the bulk region but are located at or near the
contact region of the CNT device.
CHAPTER 8
ENERGY BAND SIMULATION OF CARBON NANOTUBES

Introduction

From the gate bias insensitivity of the measured Lorentzian noise reported in chapter 7, the physical location of the noise generating trap centers was identified to be most likely the metal-CNT contact region. Similarly, the relationship between the observed 1/f noise and the gate bias level may help to identify the physical location of the associated traps as well. Although the fluctuation process associated with the 1/f noise does not have a single activation energy like Lorentzian noise, but instead interacts with a distribution of activation energies, it will be shown in the next chapter that the plot of the calculated distribution of activation energies shows a certain energy shift between two different levels of gate bias. Because the band-bending of a CNT due to the applied gate bias varies over the length of the device, it may be possible to relate the observed shift of the activation energy distribution to the band-bending due to the gate bias change and thus pin point the physical location of the associated trap centers. In order to do this, the profile of the CNT energy band at a specified gate bias, is necessary. Simulation can provide an estimate of the band-bending due to the work-function difference between the CNT and the metal contact and also due to the application of the gate voltage. Over the last few years a number of simulation strategies were proposed and validated by experimental results [47-51].
Figure 8-1. Explanation of the charge calculation using equation (8-1). (a) Symbol definition and step by step graphical representation of factors appearing in (8-1) for two cases; (b) the intrinsic and the equilibrium Fermi levels are the same and (c) when the intrinsic Fermi level is higher than the equilibrium level.
**Self Consistent Solution of Charge Density and Poisson’s Equation**

The two basic steps are (1) the calculation of charge density and (2) the calculation of potential. First the procedure for the charge density calculation will be described.

**Calculation of Charge Density**

The one dimensional charge density $\rho(x)$ is obtained from integrating the product of local density of states (DOS) and Fermi function over energy. The process is explained in Fig. 8-1 and can be expressed mathematically by [48],

$$\rho(x) = q \cdot \int D(E) \cdot \text{sign}(E) \cdot F\left[E - E_i(x)\right] \cdot \text{sign}(E) \cdot dE.$$  \hspace{1cm} (8-1)

The unit of $\rho(x)$ is in coulomb/m. Here the axial direction of the CNT is assumed to be the $x$ direction. The symbols used are described bellow,

- $-q$ is the electron charge in coulomb.
- $E$ is the variable denoting energy measured from the equilibrium Fermi level in J.
- $D(E)$ is the one dimensional density of state of CNT in $(J\cdot m)^{-1}$.
- $E_i(x)$ is the so called charge neutrality level measured from the Fermi level. In electrical engineering terminology it can be understood as the intrinsic Fermi level referenced from the equilibrium Fermi level [52].
- $\text{sign}(E)$ is the sign function defined as
  $$\text{sign}(E) = \begin{cases} 
    -1, & \text{for } E < 0, \\
    0, & \text{for } E = 0, \\
    1, & \text{for } E > 0.
  \end{cases} \hspace{1cm} (8-2)$$
- $F(E)$ is the Fermi function defined as
  $$F(E) = \frac{1}{1 + \exp(E / k_B T)} \hspace{1cm} (8-3)$$
where, \( k_B \) is the Boltzmann constant and \( T \) is temperature in K.

The density of states (DOS) is given by [47-48,53]

\[
D(E) = \frac{4}{\pi \gamma} \sum_n \frac{|E|}{\sqrt{E^2 - (\gamma \kappa_n)^2}} \cdot \Theta(\left|E\right| - \left|\gamma \kappa_n\right|) \quad \text{(J-m)}^{-1}
\]  

(8-4)

where the symbols are defined as follows,

- \( \gamma \) is the band parameter given by [29],
  \[
  \gamma = \sqrt{3a\gamma_0}/2 \quad \text{J}
  \]  
  (8-5)

where \( a = 0.24 \) nm, is the graphite lattice constant and \( \gamma_0 = 2.6 \) eV, is the nearest neighbor C-C tight binding overlap energy [29,48].

- \( \kappa_n \) is the wave number given by [48,53]
  \[
  \kappa_n = \begin{cases} 
  \frac{n - 1/3}{R}, & \text{for semiconducting CNT} \\
  \frac{n}{R}, & \text{for metallic CNT}
  \end{cases}
  \]  
  (8-6)

where, \( R \) is the CNT radius. In the presented work \( R = 0.5 \) nm is used.

- \( \Theta(E) \) is the step function defined as
  \[
  \Theta(E) = \begin{cases} 
  1, & \text{for } E \geq 0, \\
  0, & \text{for } E < 0.
  \end{cases}
  \]  
  (8-7)

The DOS plots for semiconducting and metallic CNTs using (8-4) are presented in Fig. 8-2. Note that the half band-gap \( \Delta = \gamma/3R = 0.37eV \), and the CNT radius \( R \), are used as the unit for energy and length respectively to give the reader an intuitive feel for the magnitudes involved.
Figure 8-2. Density of state plots calculated using (8-4); (a) for a semiconducting CNT (b) for a metallic CNT. The unit of the energy axis is the half band-gap, $\Delta$. 
Figure 8-3. A plot of the calculated density of carriers per unit length for metallic and semiconducting CNTs at $T = 300$K. Note that the CNT radius is used as the unit of length. For the metallic CNT, at low band-bending ($|E_i| < 1$eV) a constant DOS approximation yields sufficiently accurate result. Similarly, for a semiconducting CNT, the calculation with only the lowest sub-band is sufficiently accurate up to $|E_i| < 0.7$eV.
The one-dimensional carrier density plot calculated using (8-1) is presented in Fig. 8-3. Note, that the presence of the band-gap is clear for the semiconducting CNTs. Also it is evident from the plot that for a small band-bending, \( i.e., \) for a small \( E_i \) it is sufficient to take into account only the lowest sub-bands. The DOS for the metallic CNT considering only the lowest sub-bands with the low temperature approximation becomes a constant and is given by

\[
D(E) = \frac{4}{\pi \gamma} \nu_M (\text{J-m})^{-1}.
\]  

(8-8)

In this case, from (8-1) the charge density \( \rho(x) \) becomes linearly related to \( E_i \) and is given by

\[
\rho(x) = q \nu_M E_i(x) \quad \text{coulomb/m}. 
\]  

(8-9)

This simplifies the calculation for metallic CNTs because this leads to a closed form solution for the charge density and the corresponding band-bending, as will be shown later. This closed form solution matches very closely with the iterative solution scheme for \( T = 300\text{K} \) and with the higher sub-bands included, hence the closed form solution for the metallic CNTs was used. The calculation for the semiconducting CNTs is not straightforward even with the lowest sub-band and requires an iterative solution.

**Calculation of Potential**

The potential on the surface of the CNT is governed by Poisson’s equation. The total potential \( \phi(x) \) includes the contribution from the potential due to the charge on the CNT \( \phi^{(\rho)}(x) \), and the potential due to the gate voltage \( \phi^{(g)}(x) \), \( i.e., \)

\[
\phi(x) = \phi^{(\rho)}(x) + \phi^{(g)}(x) \quad \text{V}.
\]  

(8-10)
$\phi^{(\rho)}(x)$ and $\phi^{(g)}(x)$ are related to the charge density and the gate potential respectively via the following Fourier space relationships [47-48]:

$$\phi^{(\rho)}_k = U_k \cdot \rho_k .$$  \hspace{1cm} (8-11)

And,

$$\phi^{(g)}_k = M_k \cdot \Phi_k .$$  \hspace{1cm} (8-12)

where the symbols are defined as follows;

- $\phi^{(\rho)}_k$ is the Fourier transform of $\phi^{(\rho)}(x)$,
- $\phi^{(g)}_k$ is the Fourier transform of $\phi^{(g)}(x)$,
- $\rho_k$ is the Fourier transform of $\rho(x)$.
- $\Phi_k$ is the Fourier transform of the gate potential profile, $V_g(x) = V_g \cdot \Theta(0)$. Note $V_g$ is the gate voltage in volts and $\Theta(E)$ is the step function defined in (8-7).
- $U_k$ is the cylindrical Poisson’s kernel relating the charge density to the potential given by [47]

$$U_k = \frac{2}{\epsilon} \cdot \left( I_0(kR) \cdot K_0(kR) - I_0(kR)^2 \cdot K_0(kR_s)/I_0(kR_s) \right) .$$  \hspace{1cm} (8-13)

where $\epsilon$ is the dielectric constant of the oxide layer in Gaussian units given by $\kappa = 4\pi\epsilon\varepsilon_0$. $\varepsilon_0$ is the free space permittivity, and $\epsilon_r = 3.9$ is the relative dielectric constant of SiO$_2$. $I_0$ and $K_0$ are the modified Bessel function of the first kind. $R$ and $R_s$ are the CNT radius and the gate oxide thickness respectively. In our calculation 0.5 nm and 600 nm is used for $R$ and $R_s$ respectively.

- $M_k$ relates the gate potential to the potential on the CNT surface, given by [47],

$$M_k = I_0(kR)/I_0(kR_s) .$$  \hspace{1cm} (8-14)

- $k$ is the wave number given by
where \( L \) is the device length and \( n \) is an integer. For the devices used in the study; \( L = 1 \mu\text{m} \).

Note that the Poisson’s kernel described above is for cylindrical geometry but the device structure used in our experiments was planar. Considering the large gate oxide thickness and the order of accuracy sought, this approximation was considered sufficient.

**Self Consistent Solution Method**

The intrinsic Fermi level and the potential are related due to the conservation of the total electron energy, \( i.e., \)

\[
E_i(x) + q\phi(y) = W
\]  

(8-16)

where \( W \) is related to the work-function difference between the CNT and the contact metal. This relationship is depicted graphically in Fig. 8-1(a). Note that in our work \( W \) is assumed to be equal to the work-function difference between the CNT and the metal, which is only true for an ideal contact. We believe that this assumption of an ideal contact is sufficient as we are only interested in an order of magnitude estimate. Also the work-function of the CNT is assumed to be 4.66 eV, \( i.e. \) equal to the graphite work-function [54-55], and the work-function of Pd is 5.1 eV [34].

To enforce the boundary condition \( \phi(0) = 0 \); we use the basic idea from Odintsov et al. [47], where, anti-symmetric sources were used. In this method instead of \( W \), \( W \cdot \text{sign}(x) \) and instead of the gate voltage \( V_g \), \( V_g \cdot \text{sign}(x) \) is used and the region of space \( -L \leq x \leq L \) is solved for. Although this method forces the correct boundary condition, it requires solving a larger space (\( 2 \times \text{device length} \)). To avoid this limitation we have used a
different approach. Note that the use of the anti-symmetric sources has the effect of forcing the cosine terms in a Fourier series to zero. Hence, we use the following sine series expansion of the Fourier series and solve for only the space $0 \leq x \leq L$.

\[ \rho_k = \frac{2}{N} \sum x_i \cdot \rho(x_i) \cdot \sin(kx_i) \]  
\[ (8-17) \]

where $x_i$ is the discretized position vector and $N$ is the total number of grid point.

The inverse Fourier transform is given by

\[ \rho(x_i) = \sum_k \rho_k \cdot \sin(kx_i). \]  
\[ (8-18) \]

The simulation results presented by Odintsov et al. [47] were accurately reproduced by the simplified approach described above. The matrix size can be further reduced by observing that the charge, potential and energy profiles are symmetric across the device at zero drain bias, which means that all the even terms of the Fourier expansion will be zero and thus only the calculation of the odd terms is sufficient.

First, the closed form solution for the metallic CNT considering only the lowest sub-band will be described. Taking the Fourier transform of (8-16) and using (8-10)

\[ E_k + q\phi_k^{(\rho)} = W_k - q\phi_k^{(x)} \]  
\[ (8-19) \]

where $E_k$ and $W_k$ are the Fourier transforms of $W(x)$ and $E_i(x)$ respectively. Using (8-11) and (8-12)

\[ E_k + qU_k \cdot \rho_k = W_k - qM_k \cdot \Phi_k. \]  
\[ (8-20) \]

Using (8-9) we obtain the closed form solution for $E_k$;

\[ E_k = \frac{W_k - qM_k \cdot \Phi_k}{1 + q^2 \nu_m U_k}. \]  
\[ (8-21) \]
With all the quantities in the right hand side of the expression known, $E_i(x)$ can be calculated by evaluating (8-21) and then taking the Fourier transform.

For the iterative solution we start from (8-16). Using (8-10) and re-arranging the terms,

$$E_i(x) = W - q \phi^i(x) - q \phi^{(\rho)}(x).$$  \hspace{1cm} (8-22)

Using (8-11) and (8-12)

$$E_i(x) = W - q \cdot F^{-1}(M_k \cdot \Phi_k) - q \cdot F^{-1}(U_k \cdot F(\rho(x))).$$  \hspace{1cm} (8-23)

Since $\rho(x)$ is a function of $E_i(x)$, (8-23) can be written as the familiar vector equation, a form suitable for iteration,

$$E_i = f(E_i)$$  \hspace{1cm} (8-24)

where $E_i$ is the discretized vector form of $E_i(x)$. Now (8-24) can be solved iteratively. The flow chart of the solution scheme used is presented in Fig. 8-4.

**Results and Discussions**

The calculated band-bending for a metallic CNT at a gate voltage of 0 and +14V are shown in Fig. 8-5. Note that the noise measurements were performed at very low drain-source bias condition; hence, in the simulation the drain-source voltage is ignored *i.e.*, $V_{ds} = 0V$. Fig. 8-5 and 8-6 both show that the band-bending reaches its maximum level at the middle of the device as expected. The gate coupling is relatively weak as the maximum band-bending is only $\sim 0.7eV$ for $V_g = +14V$. The reason for this weak coupling is the large gate oxide thickness (600 nm) of the device. The plots show two distinct regions which agrees with the observation made by other researchers [47-51]. Near the contact the change in $E_i$ is abrupt, and then from $x \geq 10$ nm the changes occur at a much slower pace.
Calculate potential using (8-11) to (8-12)

If \( \Delta E_n \leq \text{Tolerance} \) STOP

Y

Calculate Charge using (8-1)

Calculate Fourier Transform: \( \rho_q, \Phi_q \)

Calculate error:
\[ \Delta E_i^n = E_i^{n+1} - E_i^n \]

Calculate new guess value:
\[ E_i^n = E_i^n - \alpha \Delta E_i^n, \quad \alpha < 1, \text{ step size for convergence} \]

Input: Initial Guess for \( E_i^n \)

Figure 8-4. Flow-chart for the iterative solution scheme.
These two regions arise because in the middle of the device the band-bending is mostly gate controlled and near the contact the effect of the gate is diminished and the effect due to the charge accumulation near the contact dominates. Also note that the use of the closed form expression to calculate the band-bending is validated by the results obtained, the use of the lowest sub-bands are sufficient enough for the small band-bending produced by the highest $V_g = +14\text{V}$.

The carrier density and the band-bending for a semiconducting CNT at $V_g = -14\text{V}$ was simulated using the iterative scheme shown in Fig. 8-4. The calculated band profile is presented in Fig. 8-6, and the resulting 1D charge density is also shown. Note that as expected, the charge density is non zero only when the equilibrium Fermi level is close to the band-edges. Also note that the band-bending near the contact for the semiconducting CNT is much more pronounced than the metallic case. This is to be expected as due to the presence of a band-gap more bending is necessary to obtain the equivalent amount of charge.

In the next chapter the application of the energy band calculation to identify the physical location of the $1/f$ noise sources will be presented.
Figure 8-5. The plot of $E_i$ vs. position at $V_g = 0$ and +14 V for a metallic CNT; (a) over full device length, $L = 1 \mu$m, and (b) close up near the left contact.
Figure 8-6. Band-bending at $V_g = +14$ V for a semiconducting CNT. $E_c$, $E_v$ and $E_i$ are the conduction band edge, valence band edge and the intrinsic Fermi level respectively. The carrier density $\rho$ is also shown.
CHAPTER 9
THERMALLY ACTIVATED 1/F NOISE IN CARBON NANOTUBES

Introduction

A brief introduction to the 1/f noise measurement was presented in chapter 2. In the beginning of this chapter the results and analysis of the 1/f noise measurement over temperature will be presented. Later an estimate of the physical location of the traps centers associated with the measured noise based on the energy band simulation discussed earlier will be presented.

The Lorentzian noise components of the two devices (devices A and B) to be discussed here were presented earlier. In this chapter the focus is on the 1/f noise these devices produce. These devices were current biased at 13.9 μA during noise measurements. This bias point was well within the linear range of device operation at all temperatures used in our experiments. For device A, the resistance changed from 0.98 kΩ at 77K to 1.04 kΩ at 300K and for device B, from 0.83 kΩ at 77K to 0.91 kΩ at 300K. This rather weak dependence of device resistance on temperature seems to indicate that a strong electron-phonon coupling is absent; lending support to a ballistic charge transport model with tunneling metal-to-nanotube contacts as proposed by Javey et al. [44].

The observed 1/f noise was calculated by subtracting the Lorentzian and the thermal noise components from the total noise as explained in Chapter 4. The 1/f noise can be expressed by Eq. (4-7) repeated here for convenience [39]

\[ S_{1/f}(f) = \frac{A \cdot I^2}{f^\beta} \]  

(9-1)
where $I$ is the dc current magnitude, $f$ is the frequency, and $A$ and $\beta$ are constants. The values of $A$ and $\beta$ are estimated by fitting a line to the experimental data as shown in Fig. 4-4. The parameter $\beta$ was found to be close, but not exactly equal, to 1.0, as expected for $1/f$-like noise. This is an indication that number fluctuation as opposed to mobility fluctuation noise dominates the measured spectra since Hooge type mobility fluctuation noise strictly requires a $\beta = 1.0$ value for Hooge’s equation to be valid [37]. The parameter $A$ represents the relative magnitude of the $1/f$ noise. As mentioned earlier, for CNTs, the parameter $A/R$ was shown to be close to a constant of $10^{-11}$ S and can serve as a figure of merit for the comparison of $1/f$ noise between different samples [7,8]. The values of $A/R$ over all temperatures of our experiment range from $1.3 \times 10^{-11}$ to $7.6 \times 10^{-11}$ S, which is within the range of values reported. The experimental values of $A$ and $\beta$ over temperature are shown in Fig. 9-1.

Calculation of the Distribution of Activation Energies

Unlike the Lorentzian noise, $1/f$ noise results when the fluctuation process does not have a single activation energy, but instead interacts with a distribution of activation energies. The plot of $A$ vs. $T$ presented in Fig. 9-2 shows peaks and valleys, that can be attributed to the non-uniform distribution in energy of the activation energies associated with the fluctuation processes.

The distribution of the activation energies $D(E)$ can be obtained from the $1/f$ noise magnitude and frequency dependence using [56]

$$D(E) \propto \frac{\omega}{k_B \cdot T} S_{1/f}(\omega, T)$$

(9-2)

where $\omega$ is the angular frequency.
Figure 9-1. Measured 1/f Noise coefficient over temperature for sample A.
The energy $E$ is calculated from

$$\tau = \tau_0 \cdot \exp\left(\frac{E}{k_B T}\right)$$

(9-3)

with $\tau_0 = 10^{-14}$ sec. Note that $E$ is rather insensitive to the value used for $\tau_0$. The calculated $D(E)$ vs. $E$ plot is shown in Fig. 9-2.

The distribution of activation energies also shows distinct peaks and valleys as expected from the $A$ vs. $T$ plot. The plot for sample B shows a broad peak around 0.45 eV, which indicates that for this sample there are a higher number of defects in this energy range. Note that activation energies for the Lorentzian components for sample B includes 0.42 and 0.51 eV which roughly corresponds to the peak shown by the $D(E)$ vs. $E$ plot. For sample A, the activation energies calculated from the Lorentzian components are lower than in sample B and roughly correspond to the peak in the $D(E)$ vs. $E$ plot as well. Please refer to chapter 7 for the activation energies of the Lorentzian components.

The frequency exponent $\beta$ can also be calculated from the magnitude of the 1/f noise using [56]

$$\beta(\omega,T) = 1 - \frac{1}{\ln(\omega \tau)} \cdot \left[ \frac{\partial \ln S_{1/f}(\omega,T)}{\partial \ln(T)} - 1 \right].$$

(9-4)

The calculated and measured values of $\beta$ are presented in Fig. 9-3.

The agreement between the calculated and measured values of $\beta$ is very good considering the fact that the values are calculated from the slopes of the $A$ vs. $T$ plot which has only a limited number of measured points. This validates the results for the energy distribution calculation.
Figure 9-2. Distributions of activation energies for sample A and B.
Figure 9-3. Measured and calculated frequency exponent $\beta$ vs. $T$ for sample A
Note that the agreement between the plots is worse at around 280K, the reason for this is again the limited number of points from which the plot is generated from. Both samples showed similar range of activation energies (Fig. 9-2) and the calculated energy range is within the range of charge transport and generation-recombination processes in CNTs.

**Physical Location of the Trap Centers**

The interpretation of the observed excess noise is further complicated by the fact that carbon CNTs operate as mesoscopic quantum devices, where traditional methods of noise measurements and interpretation may not readily apply. For example, the common 4-point probe measurement method to eliminate contact noise from the measurements will not be conclusive for a CNT device. The source and drain contact reservoirs are an integral part of a nanotube device and the addition of two more contacts may completely change the operation of the device itself [44].

A possible source of noise suggested in the literature [7-8], is the interface between the supporting oxide layer and the nanotubes. To check this possibility further, the measurement was repeated on a sample (C) containing 54 nanotubes grown under identical conditions as samples A and B, except that the oxide beneath the nanotubes was etched away so that the nanotubes were suspended in air and were not in contact with the oxide layer. No change in the magnitude of the 1/f noise was observed. The value of the factor $A/R$ for the suspended sample was $4.7 \times 10^{-11} \text{S}$, of the same order as the non-suspended sample. This rules out the oxide interface as a dominant source of excess noise.
Figure 9-4. \( D(E) \) vs. \( T \) plot calculated for \( V_g = 0 \) and \(+14V\). The trace for \( V_g = +14V \) shifted down by \( 0.04eV \) is also shown.
In Fig. 9-4, the calculated $D(E)$ vs. $E$ plot is shown for two different gate voltages, $V_g = 0V$ and $+14V$. Note that both plots show similar features. Since at $V_g = +14V$, the semiconducting CNTs do not conduct, it can be concluded that the energy distribution shown in the plot is associated with the metallic CNTs. A closer inspection of the plot also reveals that the trace of $D(E)$ for $V_g = +14V$ if shifted down by about $\sim 0.04eV$, matches with the trace of $D(E)$ for $V_g = 0V$. This indicates that the both traces, i.e., for $V_g = 0V$ and $+14V$, corresponds the same metallic CNT(s) and are associated with the same trap centers. In this case, the shift in the energy distribution $D(E)$, can be explained by the band-bending due to the application of the gate voltage. Now, from the simulation results for the metallic CNTs presented in chapter 8, an estimate of the band-bending can be obtained. The plot of the charge neutrality level, $E_i$ (or the intrinsic Fermi level) for the gate bias levels of $V_g = 0V$ and $+14V$ is shown in Fig. 8-5. $\Delta E_i$, the difference of $E_i$ between these two gate bias levels is shown in Fig. 9-5. $\Delta E_i$ is defined as,

$$\Delta E_i = E_i(V_g = 0V) - E_i(V_g = +14V).$$

The plot of $\Delta E_i$ shown in Fig. 9-5 reveals that the $0.04eV$ band-bending occurs at a distance of only $\sim 17nm$ from the contact. So it can be concluded that the defects associated with the measured 1/f noise level are physically located near the contact and thus the bulk origination of the observed noise can be ruled out. The contact region is expected to be defect rich, furthermore, due to the 1D nature of CNT, there is a limited availability of electron states in the CNT. As a result the carrier transport through the Schottky barrier at the contact will be heavily modulated by the presence of a trap centers in this region. This is may explain the high level of noise observed in CNT systems.
Figure 9-5. The difference of $E_i$ due to the change in $V_g = 0$V to +14V vs. position. The physical location at which the band-bending is equal to 0.04eV is also marked.
Since, a positive $V_g$ would shift the band down (please see Fig. 8-5), we can conclude from the positive shift of $D(E)$ for a positive $V_g$ that the traps associated have lower energy than the Fermi level. Note that the defect density distribution becomes high at very low values of $E$. This means that the most of the defects are concentrated at an energy level close to the Fermi level. Although the maximum of the $D(E)$ plot is outside of the range of the measurement range, from the plot we can estimate that the difference between the two peaks to be around $\sim 0.4$eV (the first peak is the maximum close to the origin and the second one being the broad peak around 0.4eV). This difference is once again within the range of the physical processes in the CNT system (for example, the half band-gap, $\Delta = 0.37$eV, please see Fig. 8-2). It may be possible that these two peaks correspond to the energy levels formed due to contact formation or local defect centers due to adsorption of a chemical species. For example, it has been reported that oxygen chemisorption on the surface of a (8,0) SWNT the energy gap decreased from 0.56eV to 0.23eV. However, our observation of annealing effect during CNT ablation, linked the quality of the contact to the 1/f noise level. Hence, we identify the defects associated with the formation of the contacts to be the most likely source of the observed noise phenomenon.
CHAPTER 10
CONCLUSIONS

Summary of Results and Conclusions

In the previous chapters the results and analysis of the excess noise measurements on silicon nanowires (SNW) and carbon nanotubes (CNT) were presented. In the SNW case, the excess noise was observed to have a 1/f like spectrum and the Hooge parameter, $\alpha_H$, was found to be of the order of $\sim 10^{-5}$, which is in line with modern state of art silicon processes and shows the high quality of the devices measured. In the case of the CNTs, Lorentzian spectra were observed superimposed on the 1/f noise. Recently published data estimates the $\alpha_H$ for CNTs to be $\sim 2 \times 10^{-3}$ [16-17]. Although this estimate is smaller than the previous estimate of 0.2 [7], it is still two orders of magnitude larger than the SNWs. The SNW technology is based on modern Si processes, which is considered a mature technology. The Hooge parameter in this case can be thought of as an indicator of the level of maturity of a particular technology. The Hooge parameter for mainstream silicon technology evolved from a magnitude of the order of $\sim 10^{-2}$ in the 1980’s to the value of $\sim 10^{-5}$ today. This noise reduction was achieved by improvements in the material processing techniques that resulted in defect lean materials and by well controlled and improved device fabrication processes. In comparison, the CNT technology is a novel one. It is very likely that as the CNT technology progresses towards maturity from its current nascent state, the noise figure of merit will continue to improve.

However a question can be raised about the validity of the Hooge parameter as an effective figure of merit for the noise comparison in 1D systems like CNTs. First,
consider the fact that the resistance in a CNT is mostly at the contact, the bulk resistance is generally comparatively small. Since, the ratio \( A/R \) for a CNT is close to a constant [7], two different length devices with identical \( A \) and \( R \) and bias condition would yield different values for \( \alpha_H \), because the total number of carriers might be different. The Hooge parameter should be thought of as a measure for the “per carrier” noise level. So, the physical significance of \( \alpha_H \) is diminished unless all the carriers are equally affected by the noise generating trap centers.

Hence, for a fair comparison let us compare the 1/f noise level in CNTs to the contact noise of the SNWs. The quantity \( A/R \) for the contact region of the SNW (i.e. \( A_c/R_c \)) from our noise model (presented in chapter 5) is also a constant, and from (5-20) the values for wafer 1 and 2 are \( 2.8 \times 10^{-13} \text{S} \) and \( 2.7 \times 10^{-14} \text{S} \) respectively. Comparing with the published value of \( A/R = 10^{-11} \text{S} \) for CNTs, it is apparent that the SNW has at least two orders of magnitude better noise performance than a typical CNT device. Which may be attributed to better quality contacts with a lower defect density at the contact for a SNW. As mentioned earlier the \( \alpha_H \) for the bulk noise component, is in the range of Hooge parameters for modern low noise bulk devices [40].

Our research identified the contact region as the origin of the dominant source of noise in CNT devices and also in SNWs. Note that a defect rich contact not only increases the noise level but also likely adds to the total resistance as well. This may explain the observed invariance of the \( A/R \) ratio for both CNT and SNWs. At this time the CNT technology is still nascent and the contact mechanism between the metal and the CNT is not well characterized. Because the contact was identified as the dominant source of noise, further noise reduction can envisioned by optimizing the contact. Contact
optimization may have a dramatic effect on noise because not only may it reduce the noise generating mechanism, it also may help reduce the contact resistance as well. As a result less contact noise will couple out into the remainder of the circuitry as the contact resistance becomes a smaller fraction of the total resistance.

**Future Work**

Since the contact region is identified as the most critical area for a 1D nanowire in terms of noise, a logical next step would be to focus future research on the contact mechanism in these devices with the intention of finding ways to minimize the noise level. For the Si nanowires, the next research effort should be on the quality improvement of the impinging end of the nanowire [57] since it was shown to be the likely source of the observed noise. The presence of the native oxide at the impinging end seems to critically affect both the device resistance and the noise performance, so a research project to minimize its effect may produce dramatic performance improvements.

For CNTs, more research is necessary to understand the details of the contact mechanism and the nature of the trap formation at the contact. The activation energies presented in this work may provide additional clues to determine if these activation energies can be associated with a certain physical processes. Other possible avenues, not covered in this study should also be explored. For example the gate bias dependence of the 1/f noise in a semiconducting CNT may provide important clues about noise producing mechanism as the observed noise characteristics can potentially be linked to the device characteristics operating as a FET. A detailed modeling effort, similar to what was done on SNWs in this work (chapter 5), may shed more light on the noise phenomena. The large spread in the published data on CNTs seems to indicate that the CNT devices are very much process dependent. So in order to understand the noise
mechanism and to make improvements upon the current noise level it is necessary to continue research on different type metal-CNT contacts and different processing techniques. The positive effect of annealing was demonstrated in our ablation experiment where $A/R$, the figure of merit for 1/f noise showed clear improvements due to annealing (chapter 6). So, research on similar post-processing techniques appears to be worthy of further investigation.
APPENDIX A
EQUIVALENT NOISE SOURCES OF BROOKDEAL-5004 LNA
Spectral density of the equivalent voltage source

\[ S_v(V^2/Hz) \]

Spectral density of the equivalent current source

\[ S_i(A^2/Hz) \]
APPENDIX B
FLOW CHART OF THE INSTRUMENT CONTROL PROGRAM
START

- Initialize SA
- Select Min. and Max. freq. span
- Select additional input attenuation

Set span
Set number of average

Auto range
Add input attenuation

Start measurement

Overload?

Averaging complete?

Save data

All spans complete?

Flag

Y

STOP

N

Y

N
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Shahed Reza obtained his BS in electrical engineering from the Bangladesh University of Engineering and Technology (BUET) in 1994 and then worked for Bangladesh Atomic Energy Research Establishment. He received his MS in electrical engineering from the University of Central Florida in 1998. He worked as a design engineer at Piezo Technology Inc. (PTI) from 1997 to 2000. At PTI, he designed precision crystal oscillators and LC filters. From 2000 to 2003 he designed analog microwave circuits at Agilent Technologies. As a Ph.D. candidate in the Department of Electrical and Computer Engineering at the University of Florida, Gainesville, he conducted research on the noise properties of carbon nanotubes and silicon nanowires. He is also currently working as a research engineer at Invivo Diagnostic Imaging. At Invivo, he is conducting research on image guided noise tomography and the modeling and simulation of RF probes used in MR Imaging.