[Supporting Information]

Wide Contact Structures for Low-noise Nano-channel Devices based on Carbon Nanotube Network

Hyungwoo Lee, Minbaek Lee, Seon Namgung and Seunghun Hong*

Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea

*To whom correspondence should be addressed. E-mail: seunghun@snu.ac.kr
Figure S1. Schematic diagram depicting the fabrication procedure of CNT network-based devices.
Figure S2. Structure of wide contact channel. In nano-width channel of wide contact devices, there are two kinds of CNT region. Narrow region of the channel has a width of 100nm and CNTs are aligned along the channel direction. Note that this aligned CNT network enhanced the electrical characteristics of our devices. Another region is wide contact region. CNTs near the electrode are randomly oriented since this region has a relatively large area compared to narrow channel region. Due to this wide contact region, the contact resistance and contact noise could be reduced.
**Fitting Method for Resistance of Microscale Channels based on Randomly-Oriented CNT Networks**

We assumed the CNT random network as a uniform film. Therefore, the resistance of the device could be written as

\[ R_{\text{total}} = R_{\text{ch}} + 2R_{\text{cont}} = \rho_{\text{ch}} \frac{L}{a} + \frac{r_{\text{cont}} L}{W} \]  

where \( R_{\text{ch}} \), \( R_{\text{cont}} \), \( \rho_{\text{ch}} \), \( L \), \( a \), \( r_{\text{cont}} \), and \( W \), represents the channel resistance, contact resistance between metal electrodes and CNT networks, the resistivity of CNT random network, the channel length, the cross-sectional area of the channel, the prefactor of the width-dependent term, and the contact width, respectively. We assumed that the contact resistance is inversely proportional to contact width \( W \) with \( r_{\text{cont}} \) as a prefactor. Note that the summation in front of \( \frac{L}{a} \). Since we assumed this dumbbell shaped channel is composed of 2 wide contact regions and 1 narrow channel region (Figure 2(a)), \( \frac{L}{a} \) of each region should be added up.

Here, we fabricated devices with different contact widths (contact width of 100, 20, 5, 2 \( \mu \text{m} \)) and measured the resistance of these devices. Thus, we have information of total resistance, the cross-sectional area of the channel, and the contact width for each contact width. Then, we have two unknown variables, \( r_{\text{cont}} \) and \( \rho_{\text{ch}} \).

Using above 4 kinds of data for each contact width, we could fit the measured resistance values using the equation (1) to estimate the \( r_{\text{cont}} \) and \( \rho_{\text{ch}} \). For simplicity, we rearranged the equation (1) as

\[ \frac{1}{\frac{L}{a}} \cdot R_{\text{total}} = \frac{1}{\frac{L}{a}} \cdot \frac{r_{\text{cont}} L}{W} + \rho_{\text{ch}} \]  

And we replaced the \( \frac{1}{\frac{L}{a}} \cdot R_{\text{total}} \) as \( Y \) and \( \frac{1}{\frac{L}{a}} \cdot \frac{1}{W} \) as \( X \) likewise,

\[ Y = r_{\text{cont}} \cdot X + \rho_{\text{ch}} \]  

Now we fitted this relation using measured data and we obtained Figure S3. The \( r_{\text{cont}} \) and \( \rho_{\text{ch}} \) were estimated as \( 2.58 \times 10^6 \Omega \cdot \mu\text{m} \) and \( 269 \Omega \cdot \mu\text{m} \), respectively. It allowed us to estimate channel and contact resistance (Figure 2(b)).
Figure S3. Fitting result for resistance of microscale channels based on randomly-oriented CNT networks

$Y$ and $X$ values for each device. Note that $Y$ is directly proportional to measured total resistance of devices, and $X$ is inversely proportional to contact width $W$ (equation (3)). Red line represents the fitting curve.
Fitting Method for Noise Amplitude of Microscale Channels based on Randomly-Oriented CNT Networks

The $1/f$ noise of contact resistance $R_{cont}$, which is represented by $S_{R_{cont}}$ are characterized as

$$
S_{R_{cont}} = A_{R_{cont}} \frac{R_{cont}^2}{f}
$$

(4)

If we consider the contact resistance as another source of $1/f$ noise, the total noise power spectral density $S_R$ can be written as

$$
S_R = S_{R_{ch}} + 2S_{R_{cont}}
$$

(5)

The $S_{R_{ch}}$ represents the noise power spectral density from only channel resistance $R_{ch}$ (without contact resistance $R_c$) and would be characterized as $S_{R_{ch}} = A_{R_{ch}} \frac{R_{ch}^2}{f}$. Then, the current noise power spectral density normalized for current and frequency is

$$
\frac{fS_R}{R^2} = \frac{fS_{R_{ch}}}{R_{total}^2} + \frac{fS_{R_{cont}}}{R_{total}^2} = A_{R_{ch}} \left( \frac{R_{ch}}{R_{total}} \right)^2 + 2A_{R_{cont}} \left( \frac{R_{cont}}{R_{total}} \right)^2
$$

(6)

where $R$ is total resistance of devices. Since previous works show that $\frac{A_{R_{ch}}}{R_{ch}} = \text{const}$, we assumed that $A_{R_{ch}} = \alpha \cdot R_{ch}$, where $\alpha$ is a constant. However, since the characteristics of the noise amplitude $A_{R_{cont}}$ is still unknown, we assumed that $A_{R_{cont}} = \beta \cdot R_{cont}^\gamma$, where $\beta$ and $\gamma$ are unknown constants. Then we can rewrite the equation (6) as

$$
\frac{fS_R}{R^2} = A_{total} = \alpha \cdot R_{ch} \left( \frac{R_{ch}}{R} \right)^2 + 2\beta \cdot R_{cont}^\gamma \left( \frac{R_{cont}}{R} \right)^2
$$

(7)

If we take log on both side and rearrange equation (7),

$$
\log[A_{total} \cdot R^2 - \alpha \cdot R_{ch}^3] = \log 2\beta + (\gamma + 2) \cdot \log R_{cont}
$$

(8)

Lastly we can substitute the variables of equation (8) likewise,

$$
Y = \log 2\beta + (\gamma + 2) \cdot X
$$

(9)

Here, we already have an information of $X$ and $Y$, since we have estimated $R_{cont}$, $R_{ch}$ and measured $A_{total}$, $R_{total}$ before. Only $\alpha$ should be defined as a certain initial value. Thus, we could calculate the value of $\beta$, $\gamma$. Then using the equation (7) we modified the initial value of $\alpha$. With this method, we could calculate the $\alpha$, $\beta$ and $\gamma$ iteratively. We performed this iterative calculation until the $\alpha$ was converged. In case of microscale channel based on randomly oriented CNT network, $\alpha$, $\beta$ and $\gamma$ were estimated as $1.21 \times 10^{-11}$, $7.39 \times 10^{-3}$ and $0.00824$ respectively.
Fitting Method for Resistance of Nanoscale Channels based on Aligned CNT Networks

Resistivity of aligned CNT network is known to be smaller than that of randomly-oriented CNT network. Thus we considered additional parameters of $\rho_{a,\text{ch}}$ and $R_{a,\text{ch}}$ in compared with the case of randomly-oriented CNT network channels in Equation (1). Then, total resistance $R_{\text{total}}$ of the device can be written by

$$R_{\text{total}} = R_{a,\text{ch}} + 2R_{r,\text{ch}} + 2R_{\text{cont}} = \rho_{a,\text{ch}} \frac{L}{a} + 2\rho_{r,\text{ch}} \frac{L}{a} + \frac{R_{\text{cont}}}{w}$$ (10)

where the subscripts $a,\text{ch}$ and $r,\text{ch}$ represent the aligned and randomly-oriented CNT network channel regions, respectively. $R$, $\rho$, $L$, and $a$ represent the resistance, resistivity, length, and cross-sectional area of the corresponding channel regions marked by subscripts, respectively.

Presumably, $r_{\text{cont}}$ of aligned CNT network channels would be same with that of randomly oriented CNT network channels. However, it should be noted that we applied -6V gate bias voltage to the devices. In this case, $r_{\text{cont}}$ was estimated as $1.37 \times 10^6 \, \Omega \cdot \mu m$. We already know $a$, $L$, $W$ and measured resistance values $R_{\text{total}}$. Now, we have only two unknown variables $\rho_{r,\text{ch}}$ and $\rho_{a,\text{ch}}$ in the equation (10). We fitted the equation (10) to estimate these unknown variables and obtained Figure S4. The $\rho_{r,\text{ch}}$ and $\rho_{a,\text{ch}}$ were estimated as $604.4 \, \Omega \cdot \mu m$ and $99.9 \, \Omega \cdot \mu m$, respectively. It allowed us to estimate channel and contact resistance (Figure 4(b)).

![Figure S4. Fitting result for resistance of nanoscale channels based on aligned CNT networks](image)

$Y$ and $X$ values for each devices. Note that $Y$ is directly proportional to measured total resistance of devices, and $X$ is inversely proportional to contact width $W$. Red line represents the fitting curve.
Fitting Method for Noise Amplitude of Nanoscale Channels based on Aligned CNT Networks

The fitting method for noise amplitude of nanoscale channels is basically same with microscale channels based on randomly-oriented CNT network. Therefore, we can rewrite equation (6) as

$$A_{\text{total}} = 2A_{R_{\text{ch}}} \left( \frac{R_{\text{ch}}}{R_{\text{total}}} \right)^2 + 2A_{R_{\text{cnt}}} \left( \frac{R_{\text{cnt}}}{R_{\text{total}}} \right)^2 + A_{R_{a\cdot\text{ch}}} \left( \frac{R_{a\cdot\text{ch}}}{R_{\text{total}}} \right)^2$$  \hspace{1cm} (11)

where $R$ is total resistance of devices. Here, we assumed that $A_{R_{\text{ch}}} = \alpha \times (R_{\text{ch}})^\gamma$, $A_{R_{\text{cnt}}} = \beta \times (R_{\text{cnt}})^\gamma$, and $A_{R_{a\cdot\text{ch}}} = \delta \times R_{a\cdot\text{ch}}$, where $\alpha$, $\beta$, $\gamma$, $\delta$, and $\varepsilon$ are unknown constants. Then we can rewrite the equation (11) as

$$A_{\text{total}} = 2(\alpha R_{\text{ch}}) \cdot \left( \frac{R_{\text{ch}}}{R_{\text{total}}} \right)^2 + 2(\beta R_{\text{cnt}}) \cdot \left( \frac{R_{\text{cnt}}}{R_{\text{total}}} \right)^2 + (\delta R_{a\cdot\text{ch}}) \cdot \left( \frac{R_{a\cdot\text{ch}}}{R_{\text{total}}} \right)^2$$  \hspace{1cm} (12)

At first, we estimated the $\alpha$, $\beta$, and $\gamma$ by iteratively fitting the data of the random network devices with -6V gate bias voltage as shown in Figure 3(b). Note that the equation (12) is a general equation, and the random network devices do not need the 3rd term. $\alpha$, $\beta$, and $\gamma$ were estimated as $1.14 \times 10^{-12}$, $6.88 \times 10^{-4}$, and 0.28, respectively.

Then, we utilized these parameters to further estimate two unknown constants $\delta$, $\varepsilon$ by fitting the data from the aligned network devices. In brief, we rewrite equation (12) as follows,

$$\log \left[ A_{\text{total}} \left( \frac{R_{\text{total}}}{R_{\text{ch}}} \right)^2 - 2(\alpha R_{\text{ch}}) \cdot \left( \frac{R_{\text{ch}}}{R_{\text{total}}} \right)^2 \right] = (\varepsilon + 2) \cdot \log[R_{a\cdot\text{ch}}] + \log[\delta]$$  \hspace{1cm} (13)

$$Y = (\varepsilon + 2) \cdot X + \log[\delta]$$  \hspace{1cm} (14)

By fitting the data using the equation, we could obtain values of $\delta$ and $\varepsilon$. In case of nanoscale channel based on aligned CNT network, $\delta$ and $\varepsilon$ were estimated as $1.77 \times 10^{-31}$ and 4.14 respectively.