# Electrical characterization of devices based on carbon nanotube films

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Statistical study of electrical conduction on a large array of devices based on carbon nanotube films shows a weakly dispersive film conductivity, and a specific contact resistance of 1.1 $10^{-6}$ $\Omega$ cm$^2$, which is four orders of magnitude lower than previously reported values. This allows identifying the conductivity of the carbon nanotube films as driven by a fluctuation induced tunneling mechanism. Such results pave the way to the realization of optoelectronic devices, such as highly sensitive light or gas sensor arrays. © *2010 American Institute of Physics*. [doi:10.1063/1.3350892]

Single-wall carbon nanotubes (SWCNTs) are attractive materials from both fundamental and technological points of view. Since their discovery, they have been mainly studied as individual objects especially in the nanoelectronics domain.[1,2] SWCNT field effect transistors already outperform the state-of-the-art silicon technologies in various figures of merit.[3] However devices based on individual SWCNT have very poor reproducibility, and their fabrication techniques are not yet scalable for mass production. Moreover it is currently impossible to obtain SWCNTs with controlled chirality, and the connection of these nanostructures to metal electrodes remains a challenge.[4–6] As a consequence the behavior of devices based on individual SWCNTs is unpredictable.

However, nanotube films make these difficulties disappear thanks to two characteristics: The ensemble averaging over a large number of tubes, and the large film area (typically at the semiconductor wafer scale). Thus SWCNT-films appear as a new material with unique electro-optical properties. They seem to be an appropriate candidate for flexible electronics,[7] gas sensors,[8] actuators,[9] and transparent conductive electrodes.[10] Moreover, the much larger active areas of SWCNT-films compared to those of individual SWCNTs leads to a higher sensitivity for optoelectronic devices. Itkis *et al.*[11] demonstrated the first near infrared (IR) bolometer made of a suspended millimeter-size ribbon of a 100 nm thick SWCNT-film. In this configuration when the absorbed IR radiation heats the film, a bolometric photosignal is obtained because its resistance highly depends on temperature even at room temperature. A photoresponse was also observed[12] in the mid-infrared atmospheric transmission bands (3–5 and 8–12 $\mu$m). The optoelectrical response of such devices is based on the variation of the film conductivity. Thus the contact resistance must not hinder the film resistance.

In this paper we present the electrical characterization of an array of SWCNT-film based devices. The transfer length method (TLM) is used to extract both the average specific contact resistance, and the sheet resistance of the film. The I-V characteristics are investigated over the array as a spatial uniformity criterion. We have also studied their temperature dependence, which is essential for a bolometric sensor, and sheds light on the conduction mechanisms in the SWCNT-films.

Our SWCNT-films are fabricated as follows: SWCNTs are obtained from commercial sources and their powders are dispersed in deionized water containing sodium cholate (used as surfactant). The solution is sonicated and centrifuged in order to separate the impurities from the SWCNTs. The solution is filtrated through a porous filtration membrane forming a homogenous SWCNT-film,[13] then the surfactant is washed away with deionized water, and finally the SWCNT-film is reported on the host wafer by dissolving the membrane (made of cellulose esters) with acetone.

Our samples are fabricated in four main steps.[12] First UV-patterned platinum electrodes are deposited by lift-off on a silica on silicon wafer using an e-beam evaporator. Then, as previously described a 200-nm-thick film of SWCNTs is deposited over the metallic electrodes. Next, the film is structured by $O_2$ plasma in an inductively coupled plasma system in order to define the active regions. Finally a second set of electrodes is deposited on top of the CNT mesa, and is aligned with the first one. An array of 360 identical devices

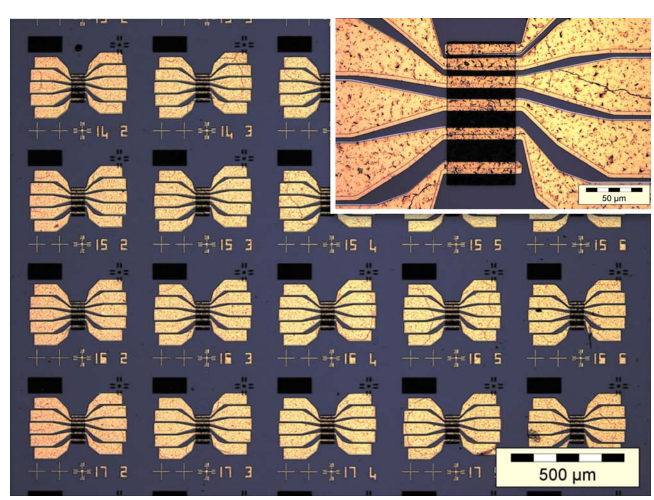


FIG. 1. (Color online) (a) Matrix of identical devices. Inset: Device with the five interelectrodes spacing $d_i$ for TLM.

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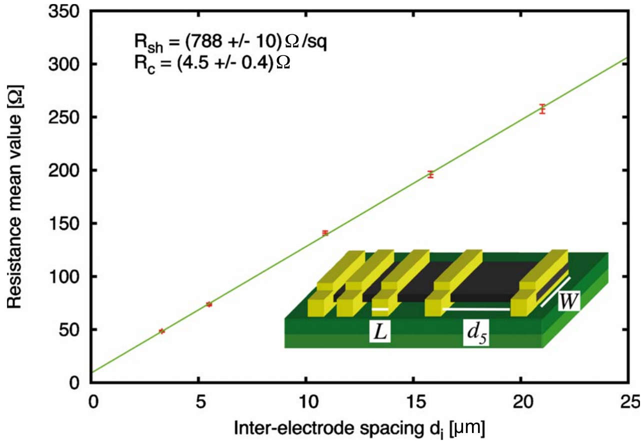


FIG. 2. (Color online) Average resistance $\langle R_i \rangle$ of each spacing vs their length $d_i$ with error bars (red). The green curve is the fit obtained with Eq. (1). Inset: Structure of a single devices.

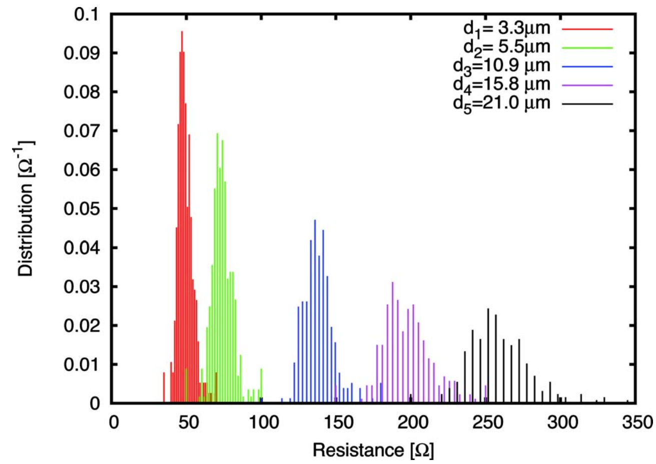


FIG. 3. (Color online) Distribution of the resistances measured among the 360 devices for each electrodes spacing $d_i$.

(Fig. 1) is fabricated on each sample. A single device, consisting of a ribbon of SWCNTs mesa (width $W=50$ $\mu$m) contacted with six double electrodes (width $L=5$ $\mu$m) defining five various spacing of length $d_i$ for TLM, is shown on the inset of Fig. 1.

The total resistance $R_i$ for a given spacing ($d_i$) is

$$R_i = 2R_c + R_{sh}\frac{d_i}{W}, \tag{1}$$

where $R_c$ is the contact resistance between the film and the metal electrodes, and $R_{sh}$ the sheet resistance. The current flowing through the SWCNT-film is transferred to the metallic contacts over the characteristic length $L_T$. Thus the contact resistance reads

$$R_c = \frac{R_{sh}L_T}{W}\coth(L/L_T). \tag{2}$$

One can also determined the specific contact resistance, $\rho_c = R_{sh}L_T^2$ which is the common geometry-independent figure of merit.

Four-probe measurements of the five spacings $d_i$ were carried out over the 360 devices of the sample. The average resistance $\langle R_i \rangle$ for each spacing $d_i$ is shown on Fig. 2. A linear fit with Eq. (1) enables to extract $R_{sh}$ and $R_c$, from which one deduces $L_T$ and $\rho_c$ (see Table I). Our technological process improves the specific contact resistance of about four orders of magnitude compared to previous work.[10] The likely explanation is the better ability of platinum to provide efficient electrical contacts as well as the process quality of the interface between the SWCNT-film and the contact electrodes. A small specific contact resistance appears as a significant improvement for bolometric applications. Indeed the contact length ($W$) could be reduced in order to increase the thermal isolation of the film and the contact width ($L$) could be submicronic [i.e., a few $L_T$ from Eq. (2)] in order to increase the device density, especially for focal plane array applications.

Since our process provides a large number of devices, we can measure the dispersion of their characteristics. Figure 3 represents, for each interelectrode spacing $d_i$, the distribution of the total resistance measured through the array. The relative dispersion is small (about 15%) but the absolute value grows with $d$. A further data processing ($R_{sh}$ and $R_c$ distributions) indicates that $R_{sh}$ is the main cause for dispersion. That is the reason why the dispersion is larger for longer spacing.

In order to investigate the temperature dependence of electrical characteristics, we performed TLM measurements on a single device for various temperatures. The contact resistance $R_c$ appears to be temperature-independent (in the uncertainties range), while $R_{sh}$ strongly decreases with temperature (Fig. 4). This decrease was already observed by other authors.[11,14–17] Nevertheless they did not extract the sheet resistance of their films, so the role of contacts was still a matter of debate.

As a matter of fact, our films are constituted of two thirds of semiconducting SWCNTs and one third of metallic ones. A percolation phenomenon makes the current flow mainly through the metallic SWCNTs[18,19] network. The tun-

TABLE I. Measured ohmic contact parameters and comparison with Ref. 10.

| | Metal | $R_{sh}$ ($\Omega$/sq) | $R_c$ ($\Omega$) | $L_T$ ($\mu$m) | $\rho_c$ ($\Omega$ cm$^2$) |
|---|---|---|---|---|---|
| Present work | Pt | $788 \pm 10$ | $4.5 \pm 0.4$ | $0.38 \pm 0.04$ | $(1.1 \pm 0.1) \times 10^{-6}$ |
| Reference 10 | Ag | 350 | 2.8 | 80 | $2 \times 10^{-2}$ |

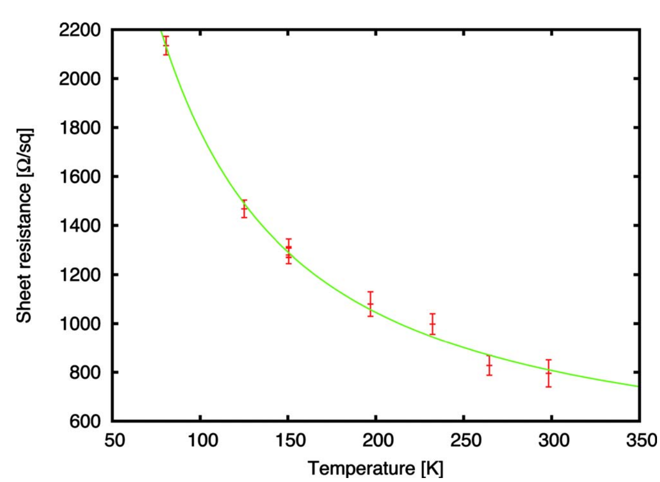


FIG. 4. (Color online) Sheet resistance with error bars vs temperature (red). The green curve is the fit obtained with Eq. (3).

neling at intertube junctions controls the film conductivity and explains the origin of the resistance decrease with temperature. P. Sheng[20] established a model of fluctuation-induced tunneling (FIT) to describe such disordered materials. In this mechanism, the effect of thermally activated voltage fluctuations across the barriers is taken into account in the tunneling process. At high temperatures the conductivity is thermally activated, and at low temperatures it becomes identical to simple (temperature-independent) elastic tunneling. In Fig. 4, the extracted $R_{sh}$ is fitted with the law provided by this model,

$$R_{sh}(T) = R_0 \exp\left(\frac{T_b}{T+T_s}\right). \tag{3}$$

The temperature $T_b$ is linked to the energy necessary for thermal fluctuations to suppress the barrier between tubes, and the $T_s/T_b$ ratio is the induced tunneling factor in absence of thermal fluctuations. As a result it appears that the temperature dependence of resistance is not due to the contact with electrodes but rather to the intertube junctions as it is suggested by the fit with Sheng's FIT model. The parameters $T_b$ and $T_s/T_b$ were found to be equal to $289 \pm 79$ K and $0.3 \pm 0.19$, respectively. Lower values[15,16] of $T_b$ have been reported (between 15 and 85 K) while published $T_s/T_b$ ratios present a large dispersion (between 0.15 and 1.4) around our result. However it is noteworthy that theses authors considered the whole resistance $R$ rather than only $R_{sh}$. Nevertheless the comparison of these values is difficult because they depend on the thickness of the film, on the type of SWCNTs used, as well as on the nature and quality of their surface state after purification, chemical doping or thermal annealing. Moreover, an increase of the resistance was sometimes observed[11,14,15,17] near room temperature, and was attributed to the metallic behavior of the conduction pathways.

Bolometric responsivity is defined by the resistance variation due to a heating. The corresponding figure of merit is the temperature coefficient of resistance (TCR), which is defined by

$$\mathrm{TCR} = \frac{1}{R}\frac{dR}{dT}. \tag{4}$$

For our SWCNT-film, TCR is found to be equal to $-0.2\%\ \mathrm{K}^{-1}$ at room temperature, which is close to data previously published for purified SWCNTs (without any special treatments to enhance the TCR) by Itkis *et al.*:[11] $\approx 0.1\%\ \mathrm{K}^{-1}$ (for a 1-$\mu$m-thick film) or by Lu *et al.*:[21] $-0.07\%\ \mathrm{K}^{-1}$ (for a 90-nm-thick film). These values are lower than those of conventional IR bolometers[22] based on amorphous silicon or vanadium oxides (TCR around $-2.5\%\ \mathrm{K}^{-1}$). However Lu *et al.*[21] demonstrated its improvement by thermal annealing and chemical functionalization.

As a conclusion, a large array of devices based on a SWCNT-film was realized. Platinum contacts on this film provide specific contact resistance as low as $1.1\ 10^{-6}\ \Omega\,\mathrm{cm}^2$, i.e., an improvement of four orders of magnitude as compared to previous works.[10] The resistance dispersion is shown to be due to the film nonuniformity, and is low enough to enable the realization of bolometer focal plane arrays. Also the conduction mechanism in the film is consistent with the FIT model, which leads to a TCR of $-0.2\%\ \mathrm{K}^{-1}$. These systems appear as promising candidates for low cost uncooled focal plane array for IR or terahertz detection.[23]

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