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# Pentacene-based thin-film transistors with multiwalled carbon nanotube source and drain electrodes

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In this letter, the authors propose a practical and reliable approach—using deposited multiwalled carbon nanotubes (MWCNTs) as source and drain electrodes—for reducing the contact resistance ($R_c$) in pentacene-based bottom-contact thin-film transistors. The value of $R_c$ of the devices was closely linked to the resultant length of the deposited MWCNTs; the lowest value was $3 \times 10^8\ \Omega\ \mu$m. The largest saturation mobility was 0.14 $cm^2/V\ s$; this value reached up to three times higher when the threshold voltage was determined using the maximum transconductance ($G_{m,max}$) extrapolation method, rather than the constant current method. The on/off ratio was more than $10^6$. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2771532]

Pentacene-based organic thin-film transistors (OTFTs) have been attracting much attention because of their relatively low cost and the feasibility of fabricating them on flexible organic substrates at low temperature. Currently, two typical device structures are employed for the fabrication of OTFTs, i.e., bottom-contact OTFT (BC-OTFT) and top-contact OTFT-(TC-OTFT). When pursuing denser electrical circuits, BC-OTFTs have an advantage over TC-OTFTs because exposure of the active organic material to solvents and chemicals can be avoided during the lithography process.[1] Nevertheless, the performance of BC-OTFTs is usually inferior to that of TC-OTFTs because of higher contact resistance ($R_c$) at the source/drain (S/D) electrodes; this phenomenon has been investigated extensively.[2,3] Carbon nanotubes (CNTs) have been the focus of much recent research because of their unique electronic properties and extraordinary mechanical properties.[4,5] Single-walled carbon nanotubes (SWCNTs) have been demonstrated as highly useful materials in nanoscale devices, while multiwalled carbon nanotubes (MWCNTs) have great potential for the field emission applications and as interconnects.[6–8]

In this letter, we propose a technique—employing thermal chemical vapor deposition (T-CVD) to deposit MWCNTs directly onto patterned S/D electrodes—for reducing the value of $R_c$ of pentacene-based BC-OTFTs; this approach appears to be more practical and reliable than that proposed in a previous study.[9] We found that the value of $R_c$ in our devices was affected strongly by the resultant length of the deposited MWCNTs. The lowest value reached $\sim 3 \times 10^8\ \Omega\ \mu$m. Not surprisingly, our fabricated devices exhibited high carrier saturation mobility ($0.14\ cm^2/V\ s$) and an on/off ratio spanning six orders of magnitude.

Figure 1 provides a schematic cross section of a BC pentacene TFT possessing an MWCNT S/D and the recipe for growth of the MWCNTs. A $n^{++}$-Si substrate was used as the gate electrode. After standard cleaning, a 320-nm-thick $SiO_2$ layer was grown thermally as the gate insulator. For S/D formation, an Fe/Ti catalytic layer was then deposited through electron beam thermal evaporation and patterned using the lift-off technique. For comparison, the Ti buffer layer was prepared at two different thicknesses (10 and 50 nm), while the thickness of the Fe layer was fixed (5 nm). Subsequently, the MWCNTs were grown through T-CVD; the procedure was performed as follows: The samples were heated to 700 °C under a nitrogen gas ($N_2$) atmosphere. After pretreatment of the Fe/Ti catalytic layer in a mixed hydrogen ($H_2$) and $N_2$ atmosphere, MWCNTs were grown on the S/D region through pyrolysis of ethylene ($C_2H_4$), as the carbon source, over two different growth times (3 and 5 min). The lengths of the MWCNTs deposited for 3 and 5 min were confirmed through scanning electron microscopy (SEM) to be ~400 nm and 1 $\mu$m, respectively. A pentacene layer (~40 nm) was finally deposited using thermal evaporation in a high vacuum chamber operated at a base pressure of

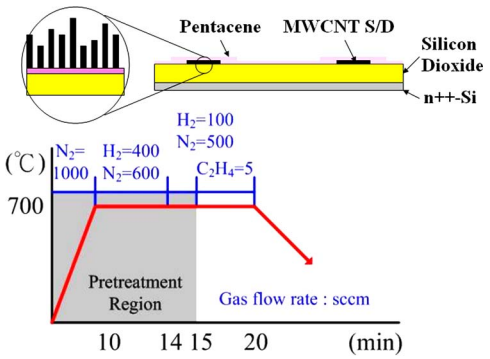


FIG. 1. (Color online) Schematic cross-sectional depiction of a pentacene BC-OTFT possessing MWCNT S/D electrodes, and the recipe for the growth of the MWCNTs.

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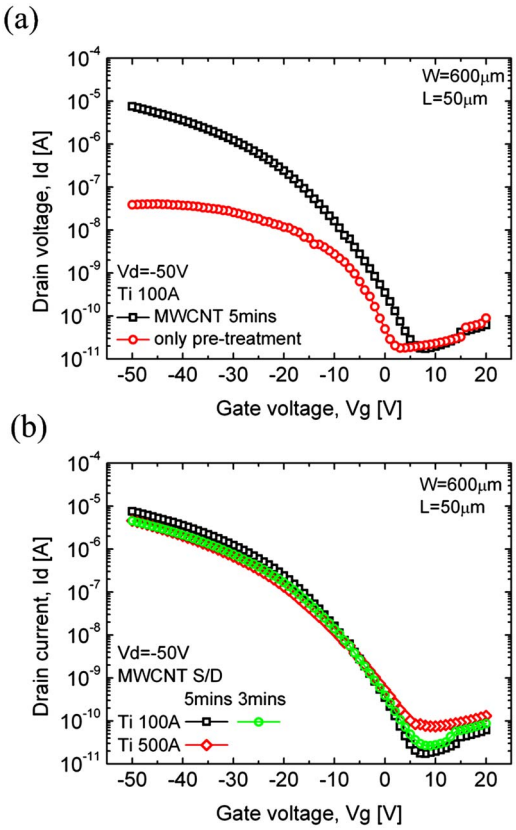


FIG. 2. (Color online) (a) $I_d$-$V_g$ characteristics of BC-OTFTs prepared with and without coverage of MWCNTs on the S/D region. (b) $I_d$-$V_g$ characteristics of BC-OTFTs plotted with respect to the MWCNT growth time and the Ti layer thickness. The channel width and length were 600 and 50 $\mu$m, respectively; the Ti layer was 10 nm thick.

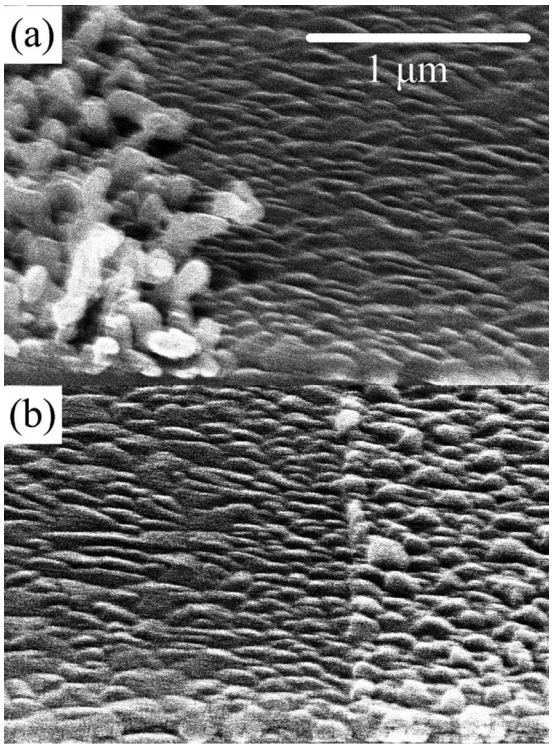


FIG. 3. SEM images of the surface morphologies after the deposition of pentacene for samples prepared using (a) 5 and (b) 3 min MWCNT growth.

$10^{-6}$ Torr at room temperature. The electrical properties of the fabricated OTFTs were characterized using a Kiethley 4200 parameter analyzer.

Figure 2(a) provides a comparison of the $I_d$-$V_g$ characteristics of the OTFTs prepared with and without MWCNT coverage on the S/D region. It is clear that the performance of the OTFTs was improved significantly after incorporating the MWCNTs. We believe that this behavior is related to three factors: (1) the difference between the work functions of Fe (~4.5 eV) and pentacene is larger than that between MWCNT (4.7±0.4 eV) and pentacene;[7] (2) the MWCNT/pentacene system probably possesses better contact properties than that of the metal/pentacene system, as might be expected from a previous finding that pentacene molecules, when deposited onto SWCNT electrodes, stack on the surface of the SWCNTs in a commensurate configuration as a result of favorable $\pi$-$\pi$ interactions;[9] and (3) the contact area induced by the presence of MWCNTs was increased tremendously. All of these factors will contribute to the smaller contact resistance and, in turn, improve the device performance. Figure 2(b) depicts the $I_d$-$V_g$ characteristics of OTFTs prepared using different MWCNT growth times and Ti layer thicknesses. The device width ($W$) and length ($L$) were 600 and 50 $\mu$m, respectively. Obviously, the BC-OTFT prepared with a longer MWCNT growth times and having a thinner Ti layer exhibited better performance; remarkably, its on/off ratio spanned six orders of magnitude. The effect of the Ti layer's thickness presumably is due to the fact that a thicker Ti layer has a larger carrier injection barrier at the interface with the pentacene active layer.[10] In terms of the effect of the MWCNTs' growth time, we suspect that a longer duration increased the length of the MWCNTs accordingly, providing a larger contact area between the pentacene layer and the MWCNT S/D electrodes. For OTFTs containing a 10-nm-thick Ti layer and 5-min-grown MWCNT, we found that the best performance was a saturation mobility of 0.14 $cm^2/V\,s$ at a value of $V_d$ of −50 V when $W$ and $L$ were 75 and 50 $\mu$m, respectively; this value was extracted from the current equation,

$$I_d = \mu_{sat} C_{ox} W (V_{GS} - V_t)^2 / 2L,$$

where $\mu_{sat}$ is the saturation mobility, $C_{ox}$ is the capacitor per unit area ($cm^2$), $V_t$ is the threshold voltage [defined as the voltage at which the drain current level is equal to $I_0(W/L)$], and $I_0$ has the magnitude of $1.67\times10^{-10}$ A. It is noteworthy that if the value of $V_t$ were determined using maximum transconductance ($G_{m,max}$) gear, the best value for the saturation mobility would be three times larger. Figure 3 displays SEM images of the surface morphologies after the deposition of pentacene for the two MWCNT growth times. We observe that pentacene had coated both the MWCNTs and the catalytic metal surfaces, and that a longer duration of growth resulted in longer MWCNTs, as expected. Moreover, we found that the two samples possessed almost identical pentacene grain structures in the channel region and near the S/D region, i.e., the transition region. As a result, we suggest that the enhanced performance of our MWCNT S/D OTFTs arose mainly from the improved contact properties, rather than from carrier transport along the channel.

Figure 4 displays the dependence of the total resistance $R_{total}$ on the channel length at different gate voltages for the sample subjected to 5 min MWCNT growth. The drain voltage was −5 V. For the channel gradual approximation[2,3] with S/D series resistance $R_{SD}$, the value of $R_{total}$ is given by

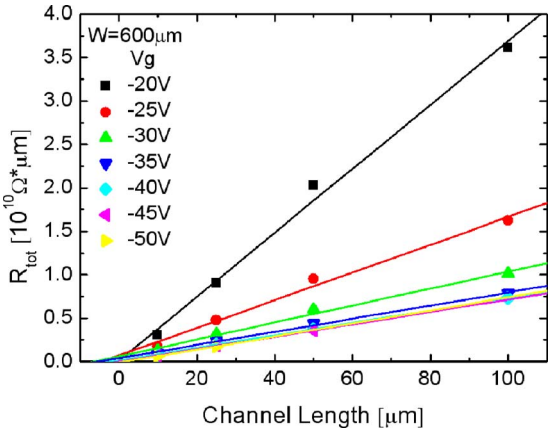


FIG. 4. Total resistance of the BC-OTFTs plotted as a function of the channel length.

$$R_{\text{total}} = V_D/I_D = R_{\text{ch}} + R_{\text{SD}} = R_{\text{SD}} + L/[W\mu_{\text{lin}}C_{\text{ox}}(V_G - V_t)],$$

where $\mu_{\text{lin}}$ is the linear-region mobility. The extracted value of the total resistance from the intercept of linear fitting was $\sim 3\times 10^8\ \Omega\ \mu$m, which is one order of magnitude lower than that of the sample subjected to 3 min MWCNT growth (data not shown).

In summary, we propose a simple and practical technique for preparing T-CVD-grown MWCNTs as S/D electrodes in pentacene-based BC-OTFTs. We found that the direct contact of the MWCNT electrodes with the pentacene channel provided excellent contact properties and a larger contact area, which, in turn, led to a relatively low contact resistance. As a consequence, the fabricated devices exhibited good electrical characteristics, i.e., high saturation mobilities and high on/off ratios.

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