1-1-2012

High-performance short channel organic transistors using densely aligned carbon nanotube array electrodes

Biddut K. Sarker
University of Central Florida

Saiful I. Khondaker
University of Central Florida

Find similar works at: <https://stars.library.ucf.edu/facultybib2010>
University of Central Florida Libraries <http://library.ucf.edu>

This Article is brought to you for free and open access by the Faculty Bibliography at STARS. It has been accepted for inclusion in Faculty Bibliography 2010s by an authorized administrator of STARS. For more information, please contact STARS@ucf.edu.

Recommended Citation

Sarker, Biddut K. and Khondaker, Saiful I., "High-performance short channel organic transistors using densely aligned carbon nanotube array electrodes" (2012). *Faculty Bibliography 2010s*. 3248.
<https://stars.library.ucf.edu/facultybib2010/3248>

High-performance short channel organic transistors using densely aligned carbon nanotube array electrodes

Cite as: Appl. Phys. Lett. **100**, 023301 (2012); <https://doi.org/10.1063/1.3675639>

Submitted: 14 November 2011 . Accepted: 16 December 2011 . Published Online: 09 January 2012

Biddut K. Sarker, and Saiful I. Khondaker

View Online

Export Citation

ARTICLES YOU MAY BE INTERESTED IN

[The effect of carbon nanotube/organic semiconductor interfacial area on the performance of organic transistors](#)

Applied Physics Letters **101**, 233302 (2012); <https://doi.org/10.1063/1.4769439>

[Suppression of short channel effect in organic thin film transistors](#)

Applied Physics Letters **91**, 113508 (2007); <https://doi.org/10.1063/1.2785118>

[Close look at charge carrier injection in polymer field-effect transistors](#)

Journal of Applied Physics **94**, 6129 (2003); <https://doi.org/10.1063/1.1613369>

Applied Physics Reviews
Now accepting original research

2017 Journal
Impact Factor:
12.894

High-performance short channel organic transistors using densely aligned carbon nanotube array electrodes

Biddut K. Sarker^{1,2} and Saiful I. Khondaker^{1,2,3,a)}

¹*Nanoscience Technology Center, University of Central Florida, 12424 Research Parkway, suite 400, Orlando, Florida 32826, USA*

²*Department of Physics, University of Central Florida, 12424 Research Parkway, suite 400, Orlando, Florida 32826, USA*

³*School of Electrical Engineering and Computer Science, University of Central Florida, 12424 Research Parkway, suite 400, Orlando, Florida 32826, USA*

(Received 14 November 2011; accepted 16 December 2011; published online 9 January 2012)

We report high-performance short channel pentacene field effect transistor (FET) using carbon nanotube aligned array electrodes. The devices show field effect mobility of up to $0.65 \text{ cm}^2/\text{Vs}$ and current on-off ratio of up to 1.7×10^6 , which is the best for sub-micron pentacene FETs. The calculated cutoff frequency (f_c) of the devices is up to 211 MHz which is among the best reported f_c for organic transistors. The high performance of our short channel FET is attributed to improved charge injections from the aligned array carbon nanotube electrodes into the pentacene. © 2012 American Institute of Physics. [doi:10.1063/1.3675639]

Organic field effect transistors (OFETs) have been considered as a promising active elements in the large area, low-cost, and low-weight electronic devices such as flexible integrated circuits, displays, sensor arrays, and radio-frequency identification tags.^{1,2} For many of these applications, OFETs should operate at high switching speed with a high on-current. The switching speed of OFETs is proportional to the mobility (μ) and inversely proportional to the square of the channel length (L).^{3,4} In addition, the on-current is also inversely proportional to the channel length. Therefore, in order to raise the switching speed and on-current, OFETs with small channel length (short channel OFETs) and high mobility are required. Up until now, short channel OFETs were fabricated using metal electrodes (mostly gold) where interfacial barriers such as Schottky barrier and dipole barrier are known to create major bottleneck for charge carrier injection.^{5,6} Both the theoretical and experimental studies reveal that when the channel length is reduced, the contact resistance at metal-organic semiconductor interface becomes very high compared to the resistance of the organic semiconductors in the channel,⁸ leading to a significant reduction in mobility. Moreover, these devices show a lower current on-off ratio due to a high off current and displays parabolic behavior in the output current, known as short channel effect.^{7,8} Therefore, achieving high performance short channel OFETs still remains a significant challenge. One way to overcome the challenges of short channel devices is to search for alternative electrode materials with more efficient charge injection into organic materials. Due to its unique electronic properties and strong π - π interaction with organic semiconductors,⁹ carbon nanotubes may be one such electrode material¹⁰⁻¹³ that can overcome the limitations of metal electrodes in fabricating high performance short channel devices.

In this paper, we report the high-performance pentacene OFETs using aligned array carbon nanotubes electrode with

$L = 0.7 \mu\text{m}$. The electronic transport measurement of 10 such devices show that the maximum mobility is $0.65 \text{ cm}^2/\text{Vs}$ with an average of $0.25 \text{ cm}^2/\text{Vs}$, and the current on-off ratio is in the range of 2.9×10^3 to 1.7×10^6 . The maximum mobility and on-off ratio reported here are the highest reported for the short channel pentacene OFETs. We also show that the calculated maximum cutoff frequency (f_c) of the device is 211 MHz with an average of 81.5 MHz. The maximum f_c of our device is one order of magnitude higher than the f_c of control and reported devices fabricated using gold electrodes. We attribute the high performance of our devices using nanotubes electrodes to improve charge injection and better interfacial contacts between pentacene and the aligned array carbon nanotube electrodes.

Highly dense aligned array single-walled carbon nanotube (SWNT) source and drain electrodes with tips parallel to each other were fabricated through oxidative cutting of aligned SWNT array by electron beam lithography (EBL) and precise oxygen plasma etching. We used heavily doped Si substrates with a thermally grown 250 nm thick SiO_2 layer as a substrate. Palladium (Pd) patterns of $5 \mu\text{m} \times 25 \mu\text{m}$, fabricated by optical lithography, were used to align the nanotubes via ac dielectrophoresis (DEP) from a high quality, stable and surfactant free SWNT aqueous solution obtained from Brewer science. The details of the SWNT assembly can be found in Ref. 14. In brief, a $3 \mu\text{l}$ drop of the solution was placed on the chip and an ac voltage of $5 \text{ V}_{\text{p-p}}$ at 300 kHz was applied between the Pd patterns for 30 s. The ac voltage creates a time averaged DEP force between Pd patterns and aligns the SWNTs. The resistances of the SWNT arrays were in the range of 400-800 Ω with sheet resistances varying from 1.5 to 3 k Ω /sq. After the assembly, the SWNT source and drain electrodes with $L = 0.7 \mu\text{m}$ and channel width $W = 25 \mu\text{m}$ were defined by EBL followed by oxygen plasma etching of the exposed SWNTs array. Finally, the samples were kept into chloroform for 12 h, and washed with isopropanol (IPA) and deionized (DI) water.

The scanning electron microscopy (SEM) image of a part of the SWNT aligned array electrodes is shown in Fig. 1(a). In

^{a)} Author to whom correspondence should be addressed. Electronic mail: saiful@ucf.edu.

FIG. 1. (Color online) (a) SEM image of a part of the nanotubes electrodes. (b) High magnification AFM image of the SWNT tips of the electrodes. AFM images of deposited pentacene thin film on the (c) nanotube electrodes, and (d) gold electrodes. The scale bars in figures (a), (b), (c), and (d) are $1\ \mu\text{m}$.

the electrodes, the nanotubes are well aligned where individual nanotubes are closely packed with parallel and open-ended tips, as shown in the atomic force microscopy (AFM) image (Fig. 1(b)). The parallel and open-ended tips are advantageous because parallel tips can enhance tunneling of the charge carriers at nanotube electrodes and pentacene interface due to electric field enhancement at these tips. In addition, open-ended tips provide higher field emission than the close-end nanotube tips.¹⁵ In order to compare the performance of our SWNT aligned array electrodes, gold electrodes of similar geometry were fabricated for control experiments. The pentacene thin film (30 nm) was thermally evaporated on top of the SWNT electrodes and gold electrodes. Figs. 1(c) and 1(d) show a part of the AFM images of the deposited pentacene thin films, showing a nearly uniform morphology throughout. We did not observe any noticeable difference between the morphologies of the pentacene films deposited on SWNT and gold electrodes. The OFET characteristics were measured using Hewlett-Packard (HP) 4145B semiconductor parametric analyzer connected to a probe station inside an enclosed glove box system with nitrogen gas flow.

The electronic transport characteristics of a typical pentacene OFET using aligned SWNT array electrodes with high mobility and high current on-off ratio are shown in Figs. 2(a) and 2(b), respectively. The transfer characteristics (Fig. 2(a)) show a well modulation of drain current (I_d) with gate voltage (V_g) with a current on-off ratio of 1.7×10^6 . The linear mobility (μ) of the device is $0.25\ \text{cm}^2/\text{Vs}$, calculated using standard formula $\mu = (L/WC_iV_d)(dI_d/dV_g)$; where, V_d is the source-drain voltage, C_i is the capacitance per unit area of the gate insulator ($13.8\ \text{nF}/\text{cm}^2$). The output

FIG. 2. (Color online). Transfer characteristics (I_d versus V_g) at $V_d = -10\ \text{V}$ (left axis) and $\sqrt{I_d}$ (right axis) of typical OFETs using (a) SWNT aligned array electrodes and (c) gold electrodes. Output characteristics (I_d versus V_d) at $V_g = 0$ to $-60\ \text{V}$ with -15 steps of the (b) SWNT aligned array electrodes and (d) gold electrodes.

characteristics (I_d - V_d curves) of the same device (Fig. 2(b)) displays a high output current of $\sim 215\ \mu\text{A}$ at $V_g = -60\ \text{V}$ and $V_d = -60\ \text{V}$. Although a high output current in the short channel OFETs is expected, well gate modulation with high on-off ratio is not typically observed in short channel OFETs using conventional metal electrodes. The linear behavior of the output curves at low bias is consistent with ideal ohmic contact, suggesting a good interfacial contact between the aligned nanotube electrode and pentacene. Out of the 10 pentacene/SWNT OFET devices that we have measured, we found that the mobilities are in the range of 0.09 to $0.65\ \text{cm}^2/\text{Vs}$ with an average of $0.25 \pm 0.16\ \text{cm}^2/\text{Vs}$ and the on-off ratios of the most of the devices are greater than 10^4 with a maximum of 1.7×10^6 . The maximum mobility of $0.65\ \text{cm}^2/\text{Vs}$ and maximum on-off ratio of 1.7×10^6 of our short channel devices using SWNT aligned array electrodes are the highest reported for any submicron pentacene OFETs.^{7,16}

The performance of our OFETs using SWNT aligned array electrodes are also better compared to our control OFETs using gold electrodes with identical device geometry, which were fabricated and measured under same experimental conditions. The transfer and output characteristics of a typical pentacene/gold device are shown in Figs. 2(c) and 2(d), respectively. The mobility, on-off ratio, and output current of this device are $0.03\ \text{cm}^2/\text{Vs}$, 1.3×10^4 , and $17\ \mu\text{A}$ (at $V_g = -60\ \text{V}$ and $V_d = -60\ \text{V}$), respectively. The mobility of the measured 10 pentacene/gold devices is in the range of 5×10^{-3} to $0.05\ \text{cm}^2/\text{Vs}$ with an average of $0.02 \pm 0.01\ \text{cm}^2/\text{Vs}$, and the on-off is in the range of 5.8×10^2 to 2.1×10^4 . Therefore, the maximum mobility and maximum on-off ratio of the devices using nanotube electrodes are ~ 13 times and ~ 100 times higher than that of devices using gold electrodes, respectively. In addition, the output curves of the OFETs using gold electrodes show a non-linear behavior at both low and high bias, a common phenomenon observed in short channel OFETs with metal electrodes and high gate thickness.^{3,4} In contrast, although our pentacene/SWNT OFETs fabricated using a small channel length ($0.7\ \mu\text{m}$) and comparable oxide thickness ($0.25\ \mu\text{m}$), they show linear behavior

of the output curves (Fig. 2(a)) and provide a higher mobility along with higher on-off ratio (Fig. 2(b)), suggesting that the performance is not limited by short channel effect. As the short channel effect is a major bottleneck in reducing the device size for high performance OFETs,^{3,4,7,8} the improvement of our short channel devices using SWNT electrodes is very significant. The performance of the OFETs mainly depends on the film morphology of the channel materials and the contact barriers between the films and electrodes. As the both the film morphologies of the pentacene/SWNT and pentacene/gold devices are the same, the improved performance of pentacene/SWNT devices are mainly arose from the improved contact.

In order to demonstrate improved charge injection of the SWNT aligned array electrodes, we show box plots of on-current of all measured pentacene/SWNT devices (top box) along with all pentacene/gold devices (bottom box) in Fig. 3(a). The on-current is calculated from the transfer curve at $V_g = -60$ V and $V_d = -10$ V. The average on-current of pentacene/SWNT devices is $65 \mu\text{A}$ with a maximum of $100 \mu\text{A}$, whereas the average on-current of pentacene/gold device is only $6.6 \mu\text{A}$ with a maximum of $11 \mu\text{A}$. Therefore, the both average and the maximum on-current of the pentacene/SWNT devices are ~ 10 times higher than that of pentacene/gold devices. This clearly demonstrates that the charge injection from densely aligned SWNT array electrodes with open ended tips is much better than that of the gold electrodes.

The short channel OFETs with high mobility can provide improved switching speed, which is required for many practical applications such as display electronics. The unity gain cutoff frequency of the transistors in the linear region is described as $f_c = (\mu V_d / 2\pi L^2) [C_i WL / (C_i WL + C_p)]$; where C_i is the gate capacitance per unit area and C_p is the parasitic capacitance. Considering $C_p \ll C_i WL$,^{3,17} we calculated f_c of our devices and a plot of the f_c versus on-off ratio is shown in Fig. 3(b). This plot shows that compared to the pentacene/

gold devices (circles), most of the pentacene/SWNT devices (stars) have a higher f_c along with a higher on-off ratio. The average f_c of the pentacene/SWNT device is 81.5 ± 54.4 MHz with a maximum of 211 MHz. On the other hand, average f_c of the pentacene/gold devices is only 6.5 ± 4.5 MHz with a maximum of 16.5 MHz. The device to device variation observed may be related to the gain size of the pentacene molecule and their orientation in the film.¹⁸ While the f_c of the pentacene/gold devices is similar to the other reported f_c using gold electrodes,¹⁹ the maximum $f_c = 211$ MHz for SWNT/pentacene OFET reported here is one order magnitude higher than that of our control device and previous reported f_c of the OFETs.^{3,17,19} Recently, it was shown that calculated value of f_c is similar to the measured value¹⁹ justifying the assumption of negligible C_p in our devices. Nevertheless, if we consider C_p is comparable $C_i WL$ in our devices, the maximum f_c of the SWNT/pentacene will be more than 100 MHz, still much higher than that of OFETs using metal electrodes.

The improved performance of our short channel OFETs using SWNT electrodes over the control and reported OFETs using gold electrodes is attributed to enhanced charge injection from aligned array SWNT electrodes. Compared to gold, carbon nanotube form a lower contact barrier with pentacene due to strong pi-pi interaction leading to higher charge injection from nanotube electrodes into the pentacene.⁹ Additionally, in contrast to gold, carbon nanotubes have electric field emission properties due to their one dimensional structure and the larger field emission comes from the nanotube tips than the side-wall.^{15,20} The open-ended tips composed of irregular-shaped graphitic sheets, which have more dangling bond on their edges than the flat edge of the usual close-ended nanotubes.²⁰ These dangling bond states have a better coupling with states of the emitted electrons which results in more emission current.^{20,21} The density of nanotubes in our aligned array electrodes is very high (~ 15 -20 SWNTs/ μm) and they are parallel to each other (Figs. 1(a) and 1(b)). Since, in our nanotubes electrodes, all the nanotube tips are open-ended fabricated through oxidative etching, the field emission of the nanotubes are enhanced.²² Therefore, a large number of parallel nanotubes with open-ended tips contribute to the field emission simultaneously resulting in higher charge injection in the devices.

In conclusion, we demonstrated high performance short channel pentacene OFETs using aligned array carbon nanotube source and drain electrodes. Our short channel OFETs with SWNT array electrode show well modulation of drain current with high on-current, high on off ratio and does not show "short channel" effect owing to improved charge injection from densely aligned SWNTs with open-ended and parallel tips. The maximum mobility of $0.65 \text{ cm}^2/\text{Vs}$ and a maximum on-off ratio of 1.7×10^6 of the OFETs reported here are higher than that of other reported short channel devices. The maximum cutoff frequency of our device is 211 MHz, which is the best reported so far for organic transistors. Our result presented here is a significant step forward in fabricating high performance organic electronic devices.

This work is supported by U.S. National Science Foundation under Grant ECCS 1102228.

FIG. 3. (Color online) (a) Box plot of the on-current of pentacene/SWNT (top box) and pentacene/gold devices (bottom box). (b) Cutoff frequency is plotted against corresponding current on-off ratio for 10 pentacene/SWNT devices (star) and 10 pentacene/gold devices (circle).

- ¹A. Dodabalapur, *Mater. Today* **9**, 24 (2006).
- ²B. Crone, A. Dodabalapur, Y. Y. Lin, R. W. Filas, Z. Bao, A. LaDuca, R. Sarpeshkar, H. E. Katz, and W. Li, *Nature (London)* **403**, 521 (2000).
- ³J. Collet, O. Tharaud, A. Chapoton, and D. Vuillaume, *Appl. Phys. Lett.* **76**, 1941 (2000).
- ⁴J. Z. Wang, Z. H. Zheng, and H. Sirringhaus, *Appl. Phys. Lett.* **89**, 083513 (2006).
- ⁵N. Koch, A. Kahn, J. Ghijsen, J. J. Pireaux, J. Schwartz, R. L. Johnson, and A. Elschner, *Appl. Phys. Lett.* **82**, 70 (2003).
- ⁶T. G. Hill, A. Rajagopal, A. Kahn, and Y. Hu, *Appl. Phys. Lett.* **73**, 662 (1998).
- ⁷L. Wang, D. Fine, T. Jung, D. Basu, H. v. Seggern, and A. Dodabalapur, *Appl. Phys. Lett.* **85**, 1772 (2004).
- ⁸L. Burgi, T. J. Richards, R. H. Friend, and H. Sirringhaus, *J. Appl. Phys.* **94**, 6129 (2003).
- ⁹C. Chia-Hao, C. Chao-Hsin, and Y. Jung-Yen, *Appl. Phys. Lett.* **91**, 083502 (2007).
- ¹⁰P. F. Qi, A. Javey, M. Rolandi, Q. Wang, E. Yenilmez, and H. J. Dai, *J. Am. Chem. Soc.* **126**, 11774 (2004).
- ¹¹C. M. Aguirre, C. Ternon, M. Paillet, P. Desjardins, and R. Martel, *Nano Lett.* **9**, 1457 (2009).
- ¹²S. L. Hellstrom, R. Z. Jin, R. M. Stoltenberg, and Z. Bao, *Adv. Mater.* **22**, 4204 (2010).
- ¹³B. K. Sarker, J. Liu, L. Zhai, and S. I. Khondaker, *ACS Appl. Mater. Interfaces* **3**, 1180 (2011).
- ¹⁴S. Shekhar, P. Stokes, and S. I. Khondaker, *ACS Nano* **5**, 1739 (2011).
- ¹⁵G. Zhou, W. Duan, and B. Gu, *Phys. Rev. Lett.* **87**, 095504 (2011).
- ¹⁶U. Haas, H. Gold, A. Haase, G. Jakopic, and B. Stadlober, *Appl. Phys. Lett.* **91**, 043511 (2007).
- ¹⁷V. Wagner, P. Wöbkenberg, A. Hoppe, and J. Seekamp, *Appl. Phys. Lett.* **89**, 243515 (2006).
- ¹⁸B. Bräuer, R. Kukreja, A. Virkar, H. B. Akkerman, A. Fognini, T. Tylliszczak, and Z. Bao, *Org. Electron* **12**, 1936 (2011).
- ¹⁹R. Rotzoll, S. Mohapatra, V. Olariu, R. Wenz, M. Grigas, K. Dimmler, O. Shchekin, and A. Dodabalapur, *Appl. Phys. Lett.* **88**, 123502 (2006).
- ²⁰M. S. Wang, L. M. Peng, J. Y. Wang, C. H. Jin, and Q. Chen, *J. Phys. Chem. B* **110**, 9397 (2006).
- ²¹K. Tada and K. Watanabe, *Phys. Rev. Lett.* **88**, 127601 (2002).
- ²²A. G. Rinzler, J. H. Hafner, P. Nikolaev, P. Nordlander, D. T. Colbert, R. E. Smalley, L. Lou, S. G. Kim, and D. Tománek, *Science* **269**, 1550 (1995).