PERGAMON

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Solid-State Electronics 47 (2003) 1855–1858

SOLID-STATE ELECTRONICS

www.elsevier.com/locate/sse

Depletion-mode n-channel organic field-effect transistors based on NTCDA

Mo Zhu, Guirong Liang, Tianhong Cui *, Kody Varahramyan

Institute for Micromanufacturing, Louisiana Tech University, P.O. Box 10137, 911 Hergot Avenue, Ruston, LA 71272, USA

Received 15 March 2003; accepted 3 April 2003

Abstract

The depletion-mode n-channel organic field-effect transistors (OFETs) based on naphthalene-tetracarboxylic-dianhydride (NTCDA) were fabricated and characterized. Electrical characteristics of the OFETs were demonstrated and analyzed under the depletion-mode operation. The mobility of NTCDA is about 0.016 $cm^2\,V^{-1}\,s^{-1}$. The threshold voltage is −32 V, and cut off current is 1.76 nA. The on/off ratio extracted from transfer characteristics at saturation region ($V_{ds} = 60$ V) is 2.25×10^2.

Keywords: NTCDA; Organic field-effect transistor (OFET); Depletion-mode; Energy level

1. Introduction

Conductive organic materials have been widely investigated for the applications to the areas of microelectronics and optoelectronics, such as transistors and light emitting diodes [1,2] due to their well-known advantages, such as low cost and flexibility.

Currently most of the studies on organic microelectronic/optoelectronic devices are based on p-type materials like pentacene [3], α-sexithiophene (α-6T) [4], etc. Normally p-type organic materials are more stable than n-type organic materials, and shows higher carrier mobility. The reported highest carrier mobility to our knowledge is 3 $cm^2\,V^{-1}\,s^{-1}$ in pentacene [5]. Compared to p-type organic materials, n-type organic materials have much lower mobility, and are more sensitive to the environments due to the transport mechanism of organic materials. Among several n-type materials, naphthalene-tetracarboxylic-dianhydride (NTCDA) is more promising due to its high mobility of 0.06 $cm^2\,V^{-1}\,s^{-1}$ [6] and investigated stabilities [7].

In this paper, the depletion-mode n-channel organic field-effect transistors (OFETs) based on NTCDA are fabricated and characterized. From the discussions and analyses of charge transport and energy bands, the mechanism and function of this OFET are introduced and demonstrated.

2. Experiments

2.1. Materials

In the fabricated transistors, NTCDA acts as active channel material due to its n-type conduction [7]. P-type conductive polymer polypyrrole (PPy) performs as the source and the drain in the transistors, showing good characteristics of the p-type conducting polymer [8]. Aluminum is as the electrodes for the source and the drain. Dielectric material is poly(4-vinylphenol) (PVP) dissolved in isopropanal alcohol. All the organic chemicals, undoped NTCDA powder, 20 wt.% PPy aqueous solution, and PVP solution, are purchased from Aldrich. Fig. 1 shows the molecular structures of NTCDA and PPy.

* Corresponding author. Tel.: +1-318-257-5122; fax: +1-318-257-5104.
E-mail address: tcui@coes.latech.edu (T. Cui).

0038-1101/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0038-1101(03)00141-2

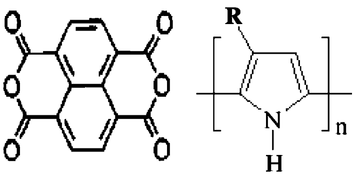

Fig. 1. Molecular structures of NTCDA (left) and PPy (right).

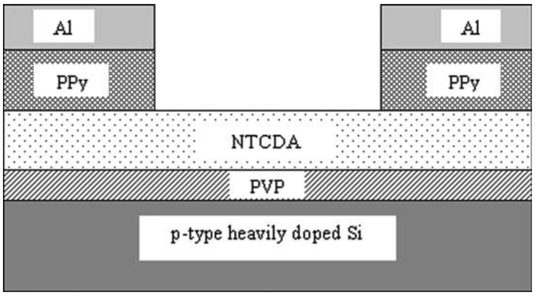

Fig. 2. Top contact (TOC) device structure.

2.2. Fabrication

Normally, OFETs adopt two kinds of structures, bottom contact (BOC) and top contact (TOC) [9]. Here the TOC structure was employed in the devices, as illustrated in Fig. 2. The width of channel is 40 μm, and the length is 200 μm.

As shown in the schematic figure, the devices are built on the heavily doped silicon wafer, which also acts as the gate electrode. First, a layer of PVP 800 nm thick is spun on the wafer. A permittivity of 12.4 is determined. Next, NTCDA 1.5 μm thick is thermally evaporated at the current of 20 amp and the working pressure of 1×10^{-7} Torr. After the evaporation of NTCDA, PPy is deposited by spin-coating and Al 200 nm thick is thermally evaporated on top of PPy. Lithography process is used to pattern Al, and RIE (reactive ion etching) process to form the source region and the drain region.

3. Results

NTCDA-based OFETs were characterized in the atmosphere using KEITHLEY TEST SYSTEM (236 Source Measure Unit). Figs. 3 and 4 plot the electrical output and transfer characteristics, respectively. In Fig. 3, the drain current (I_d) versus the drain voltage (V_{ds}) curve (output characteristics) shows the depletion-mode operation. With the decrease of gate voltage, the drain current (I_d) correspondently decreases step by step. The drain current (I_d) versus the gate voltage (V_{gs}), transfer characteristics, at linear output region ($V_{ds} = 20$ V) are shown in Fig. 4(a), demonstrating the threshold voltage

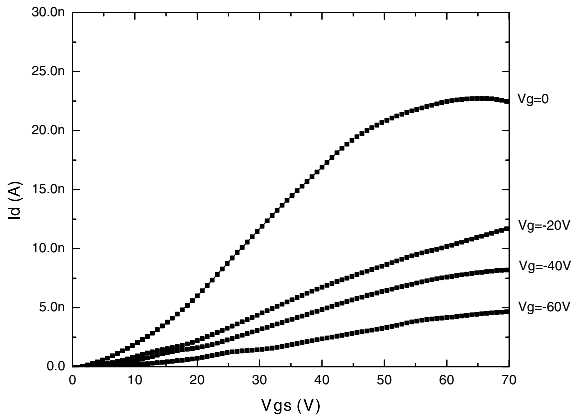

Fig. 3. I_d versus V_{gs} curve of the OFET using NTCDA as the semiconductor and PPy as the gate.

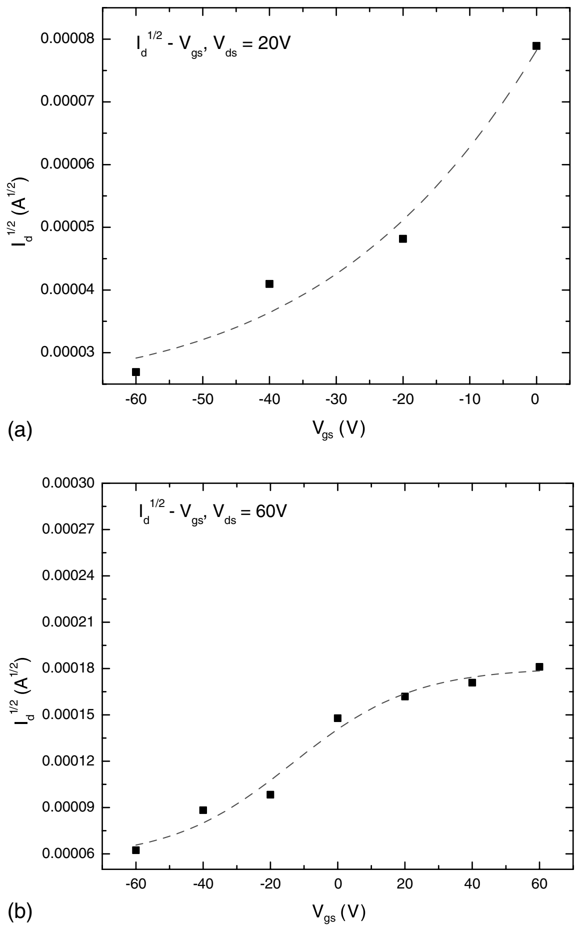

Fig. 4. Transfer characteristics at $V_{ds} = 20$ V (top) and $V_{ds} = 60$ V (bottom).

of −32 V and the cut off current of 1.76 nA. The on/off ratio extracted from the transfer characteristics at the saturation region ($V_{ds} = 60$ V) is about 2.25×10^2, as shown in Fig. 4(b). The electron mobility is calculated to be 0.016 $cm^2 V^{-1} s^{-1}$ from the models discussed in the next section, which is smaller than the results from the doped NTCDA [1] and larger than the former investigated undoped one [10].

4. Discussions

The depletion-mode FETs are normally on due to the electric field built by the existed electrons in the channel region between the source and the drain. For this type of device, it is functional, even though gate voltage (V_{gs}) is equal to zero. With the decrease of V_{gs} (V_{gs} is negative), the effective channel shrinks, and thus conduction ability of the active layer decreases simultaneously. Therefore the drain current (I_d) decreases until the active channel disappears, and then the device is cut off. The gate voltage that turns off the device is known as the turn-off voltage, which is also the threshold voltage where the active channel forms.

The traditional device models based on inorganic materials can still describe the devices made of organic materials, the equation for the linear region is [11]

$$I_d = \mu C_{ox} \left(\frac{W}{L} \right) \left(V_{gs} - V_{th} - \frac{1}{2} V_{ds} \right) V_{ds} \tag{1}$$

For the saturation region, the equation is

$$I_d = \frac{1}{2} \mu C_{ox} \left(\frac{W}{L} \right) (V_{gs} - V_{th})^2 \tag{2}$$

where W and L are the channel width and lengths respectively, μ is the carrier mobility of the n-channel device, C_{ox} is the capacitance per unit area of the dielectric layer, and V_{th} is the threshold voltage. The electron mobility calculated from Eqs. (1) and (2) gives the rough estimation compared to the traditional inorganic devices.

From the energy-band theory and the interfacial effect, the insight of the OFET can be analyzed. Table 1 [12,13] gives the parameters (work function Φ, energy gap E_g, and Fermi level or effective Fermi level E_F) of the materials used in the fabricated OFETs. Fig. 5 illustrates the interfacial energy structure with alignment and bending. At the gate voltage of zero, the channel is completely open, and the electrons can be injected into the channel without barriers. The higher the drain current (V_{ds}), the more electrons injected, and the larger drain current until the channel becomes saturation. When the gate voltage is decreased, the conduction band of heavily doped silicon will rise above the lowest unoccupied molecular orbital (LUMO) of NTCDA, thus the positive charges are accumulated in the interface and negative charges are partially depleted in the channel. Moreover, the capability of electron-activated n-type channel is weakened. If the gate voltage is below the threshold voltage, the channel will turns off, and the drain current will not be generated even collected with the high drain voltage.

Table 1
Parameters of used materials

Materials	Φ (eV)	E_g (eV)	E_C (LUMO) (eV)
NTCDA [12]	3.97	3.3	3.6
PPy [13]	5.19	3.16	2.5
P-type heavily doped Si	5.11	1.12	4.05

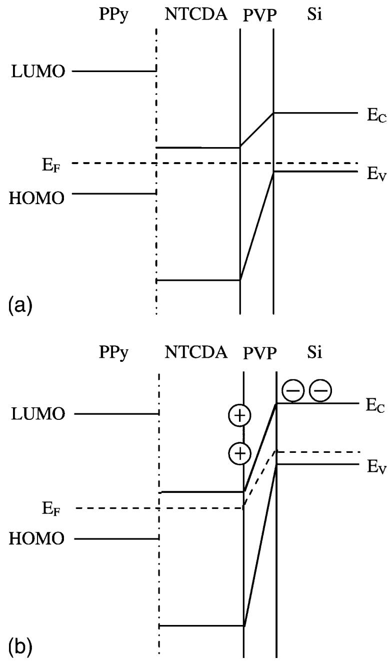

Fig. 5. Interfacial alignment for zero gate voltage (a) and negative gate voltage (b).

Another point is that the conducting channel is inside the bulk of the active layer of the depletion-mode operated devices compared to the channel at the interface between the dielectric layer and the active layer of the accumulation-mode operated devices, especially for the TOC structure. Fig. 5(b) clearly shows that the n-channel will be turned off from the gate side to the source/drain side when the negative gate voltage is applied.

One of the most important applications of the depletion-mode OFETs is as the load device of the inverter due to the symmetrical charging and discharging time constants [14], much faster than the inverter with enhancement-mode transistors. Thus the depletion-mode OFETs can be used in the organic integrated circuits.

5. Conclusions

In this paper the depletion-mode n-channel organic FETs based on NTCDA have been presented. Moreover, given the energy structures and interfacial alignments of this type of device, the electrical characteristics are analyzed and discussed. The mobility of 0.016 $cm^2\,V^{-1}\,s^{-1}$ is obtained. The threshold voltage is −32 V, and cut off current is 1.76 nA. The on/off ratio at saturation region ($V_{ds} = 60$ V) is 2.25×10^2. The environment effects (temperature, humidity, etc.) to the electrical properties of NTCDA will be under investigation. Further research to improve the properties of the OFETs may focus on the n-type organic semiconductors with higher carrier field-effect mobility, organic dielectrics with better quality, and conductive polymers with higher conductivity as the electrodes.

Acknowledgements

This work is partially supported by the DARPA, DAAD19-02-1-0338 and CEnIT seed grant at Louisiana Tech University.

References

[1] Dimitrakopoulos CD, Mascaro DJ. Organic thin-film transistors: a review of recent advances. IBM J Res Dev 2001;45(1):11–27.

[2] Tang CW, Vanslyke SA. Appl Phys Lett 1987;51:913.

[3] Klauk H et al. Pentacene organic thin-film transistors and ICs. Solid State Technol 2000;43(3):63–77.

[4] Garnier F, Hajlaoui R, Yassar A, Srivastave P. Polymer field-effect transistors realized by printing techniques. Science 1994;265:1684–6.

[5] Klauk H et al. Polymer gate dielectric pentacene TFTs and circuits on flexible substrates. International Electron Devices Meeting, San Francisco, CA, 22.1.1–22.1.4, December 8–11, 2002. p. 557–60.

[6] Katz HE et al. A soluble and air-stable organic semiconductor with high electron mobility. Nature 2000;404(30): 478–80.

[7] Torsi L et al. NTCDA organic thin-film-transistor as humidity sensor: weaknesses and strengths. Sens Actuators B 2001;3830:1–5.

[8] Liang G, Cui T, Varahramyan K. Electrical characteristics of diodes fabricated with organic semiconductors. Microelectron Eng 2003;65:279–84.

[9] Roichman Y, Tessler N. Structures of polymer field-effect transistor: experimental and numerical analyses. Appl Phys Lett 2002;80:151–3.

[10] Laquindanum JG, Katz HE, Dodabalapur A, Lovinger AJ. N-channel organic transistor materials based on naphthalene frameworks. J Am Chem Soc 1996;118: 11331–2.

[11] Arora N. MOSFET models for VLSI circuit simulation: theory and practice. Wien, New York: Springer-Verlag; 1993.

[12] Nollau A, Pfeiffer M, Fritz T, Leo K. Controlled n-type doping of a molecular organic semiconductor: naphthalenetetracarboxylic dianhydride (NTCDA) doped with bis(ethylenedithio)-tetrathiafulvalene (BEDT-TTF). J Appl Phys 2000;87(9):4340–3.

[13] Cassagneau T, Mallouk TE, Fendler JH. Layer-by-layer assembly of thin film Zener diodes from conducting polymers and CdSe nanoparticles. J Am Chem Soc 1998; 120:7848–59.

[14] Yang ES. Microelectronic devices. McGraw-Hill; 1988.