Implementation of Low-Voltage Operation of Pentacene Thin Film Transistors using a self-grown metal-oxide as gate dielectric

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Abstract

we implemented pentacene TFTs able to operate at low voltage less than 2V by using ultra-thin Al2O3 layer as a gate insulator. The OTFTs exhibited a mobility of 0.27±0.05 cm^2/Vs*, an outstanding subthreshold slope of 0.109±0.027, and an on/off current ratio of* $2.87\pm1.07x10^4$*. OTFT operated at low voltage, producing 3.5uA at* $V_{GS} = 2V$ *and* $V_{DS} = 1.5V$*.*

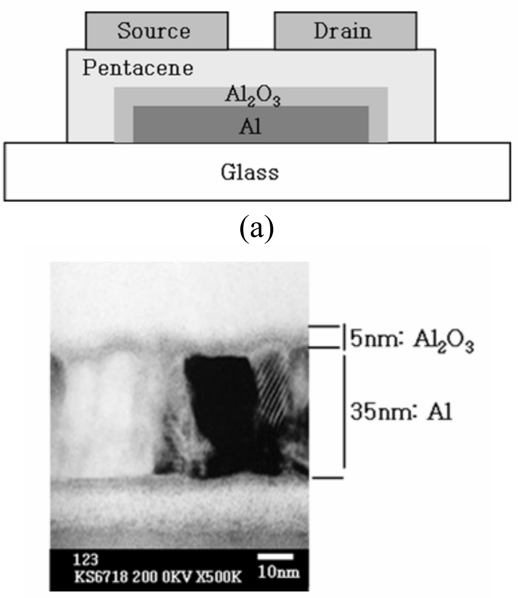
1. Objectives and Background

The organic thin film transistors are mature to be applied to backplane of flexible displays and RFIDs[1-7]. However a major problem is that current devices require high voltages to operate. The key to low-voltage operation is to decrease the thickness of gate dielectric. Researches to realize a thinner gate dielectric layer have been continuously carried out [8]. The Infenion group reported 2.5nm-thick molecular self-assembled monolayer (SAM) gate dielectric on a heavily doped silicon substrate[9]. However, this may not be commercially feasible since there is no plan to electrically isolate the devices when the heavily doped silicon substrate is used for gate electrodes. Another paper, proposed anodization of metal to form metal oxide with a thickness of several nanometers as a gate dielectric layer[10]. However, this may lack usability since anodization, a kind of wet process, may often invite an unfavorable peeling of metal. It is therefore required to develop an advanced organic thin film transistor that allows forming an ultra-thin gate dielectric layer in low-temperature process and further permits a low-voltage operation. It is also required to develop an advanced organic thin film transistor that enables IC fabrication and thus is available for flexible displays, RFID, etc.

Here we report the development of an ultra-thin gate dielectric for low voltage operation of OTFTs by directly oxidizing the pre-existed gate electrode with O_2 plasma process, achieving nano-thick Al2O3 gate dielectric. Thus, the OTFTs do not need the additional patterning process for the gate dielectric layer. So the fabrication processes are thereby simplified.

2. Experimental

The fabrication processes were as follows. While a glass substrate was employed in this work, plastic substrates can be applied because the process is performed at room temperature and strong solvents are not used. First, an aluminum gate electrode was deposited on the substrate through a metal shadow mask by thermal evaporation. Then Al2O3 gate dielectric layer formed by O2 plasma process. The O2 plasma process was carried out for 10min, 60min at 145mTorr pressure with 10sccm O2 flow rate and 150W power. A pentacene active layer was then deposited by thermal evaporation with a grow rate of 0.3Å/sec up to 45nm thickness at a substrate temperature of 80℃. Finally source and drain electrodes were evaporated on the pentacene active layer yielding bottom gate and top contact structure as shown in Fig. 1(a).



(a)

(b)

Figure 1. (a) The device structure of low voltage pentacene TFTs and (b) TEM image of self-grown Al2O3 insulator and bottom Al gate electrode.

3. Results and Discussion

The thickness of the self-grown Al2O3 was about 5nm, as shown in Fig. 1(b). The leakage current through the Al2O3 layer was measured using a metal-insulator-metal(MIM) structure device. Considering the current transport equation with the measured I-V curves, shown in Fig. 2, the transport mechanism appears to be direct tunneling in the low voltage region from 0V to 0.5V. Meanwhile, in the high voltage region above 1.34V, the transport mechanism is determined to be Fowler-Nordheim(FN) tunneling. The I-V curve of the Al-Al2O3-Al device was symmetric along the positive and negative voltage axes. However, for the Al-Al2O3-Au device, the I-V curve was asymmetric. The change in the I-V curve is attributed to the work function difference between the bottom Al and the top Au electrode, which produces a built-in electric field across the Al2O3 layer.

The breakdown electric field was roughly 3MV/cm, comparable to Al2O3 grown by rf magnetron sputtering[11]. The capacitance was 1.1×10^{-6}F/cm^2 at 1MHz. The dielectric constant k extracted from the relationship $C=k\varepsilon_o/d$ was about 6.2, which is small in comparison with the typical value of sputtering-grown Al2O3, at 7[11].

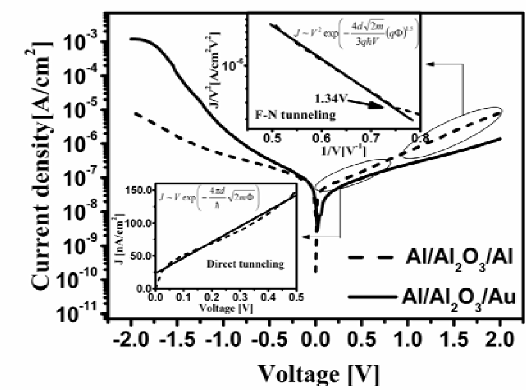
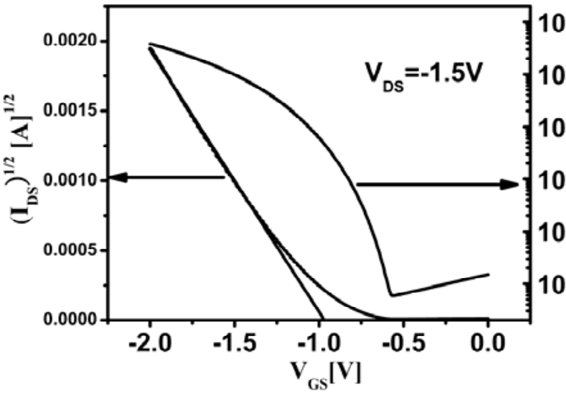
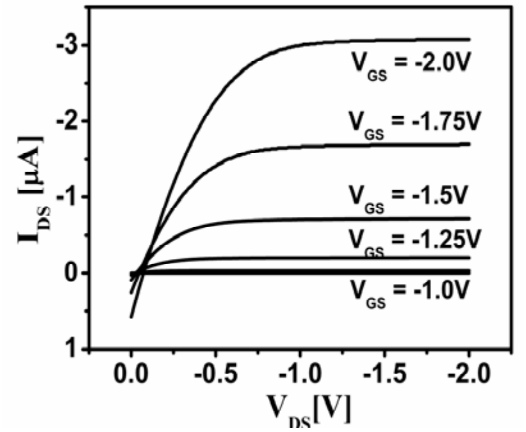


Figure 2. Comparison of current-voltage curves for Al-Al2O3-Al and Al-Al2O3-Au MIM devices; the insets represent the enlarged direct tunneling and FN tunneling relationship of the Al-Al2O3-Al case.

The OTFTs employing a self-grown Al2O3 gate dielectric operated at low voltage, producing 3.5uA at V_{GS} = 2V and V_{DS} = 1.5V for W/L=1035μm/34μm. The threshold voltage was small at -0.97±0.04 V, the subthreshold slop was 0.109±0.027 V/dec, the mobility was 0.27±0.05 cm^2/Vs and the on/off current ratio was 2.87±1.07 x10^4 for the 60min oxygen plasma process.



(a)



(b)

Figure 3. (a)Transfer and (b)output characteristics of pentacene TFTs using ultra-thin Al2O3 gate dielectric with a 1035μm channel width and 34μm channel length, which was produced by oxygen plasma for 60min.

The drain saturation current at VGS=-2V and VDS=-1.5V was plotted with respect to channel length and width, as shown Fig. 4, to examine device behavior according to channel scaling. The drain saturation current was inversely proportional to channel length and linearly proportional to channel width. Thus, we found that the devices behaved very well down to 10μm of channel length. The threshold voltage was highly uniform independent of the channel width.

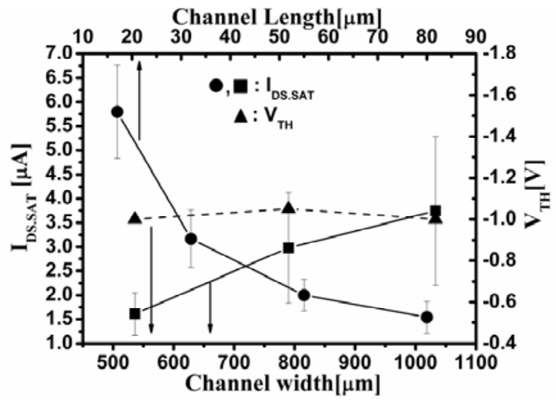
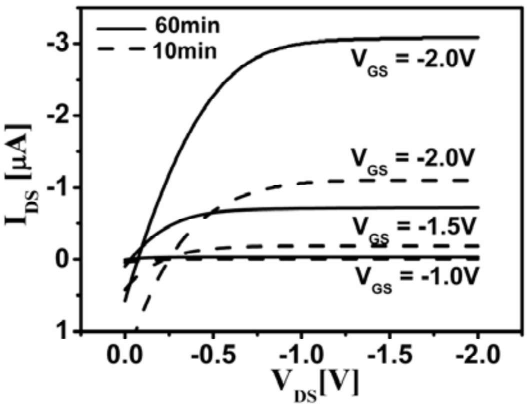
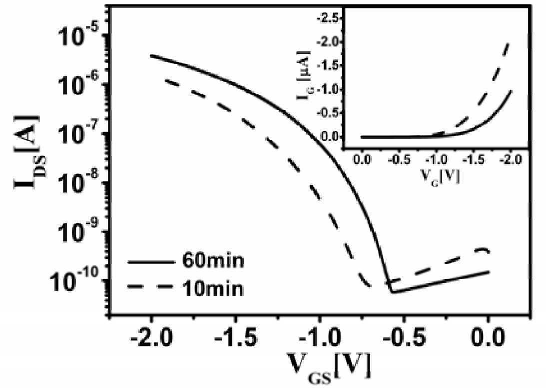


Figure 4. The scaling behavior of low voltage OTFTs with various channel length L(●) and width W(■), but the threshold voltage is uniform independent of the channel width(▲).

In the output curve the drain current does not converge to 0A but rather the current direction changes as V_{DS} approaches 0V, as shown in Fig. 5(a). This is attributed to the gate leakage current and is enhanced as V_{GS} increases. This current direction change disappeared as the oxygen plasma time was increased from 10min to 60min. This improvement is due to a reduction of the gate leakage current, as shown in the inset of Fig. 5(b). For the 10min oxygen plasma process, the OTFTs exhibited that the performance parameters were inferior to the former. The threshold voltage was -1.18±0.027 V, the subthreshod slop was 0.16±0.019 V/dec, the mobility was 0.12±0.015 cm^2/Vs and the on/off current ration was 8.76±5.3 $x10^3$. The degradation was also attributed to the gate leakage. It is believed that the thickness of Al2O3 layer increases with the oxygen plasma time. The effects of oxygen plasma on performance are currently under investigation.



(a)



(b)

Figure 5. Comparison of (a)output and (b)transfer characteristics of pentacene TFTs using ultra-thin Al2O3 gate dielectric which was produced by oxygen plasma for 10, 60min; the inset of (b) is a comparison of the gate leakage currents.

4. Conclusion

We developed a simple fabrication method to implement low voltage operation of pentacene TFTs. The method utilizes a few nanometer thick Al2O3 layer as a gate dielectric. Additionally, since the nano-thick Al2O3 is directly grown on the pre-existed Al gate electrode, the additional gate patterning process is not necessary, thereby the overall fabrication process is simplified. The performance of pentacene TFTs was acceptable, with a mobility of 0.27 $cm^2/V.s$ and as on/off current ration of 10^4. Furthermore, it involves a low temperature, dry process, there by allowing for low-cost fabrication and flexible applications.

5. Acknowledgements

This work was supported by the Information Display R&D Center as part of the 21st Century Frontier R&D Program funded by the Ministry of Commerce, Industry and Energy of Korea.

5. References

[1] S. R. Forrest, Nature **428**, 911 (2004).

[2] B. Crone, A. Dodabalapur, Y. Y. Lin, R. W. Filas, Z. Bao, A. Laduca, R. Sarpeshkar, H. E. Kate, and W. Li, Nature **403**, 521 (2000).

[3] H. E. A. Huitema, G. H. Gelinck, J. B. P. H. Van der Putten, K. E. Kuijk, C. M. Hart, E. Cantatore, P. T. Herwig, A. J. J. M. Van Breemen, and D. M. De Leeuw, Nature **4**, 599 (2001).

[4] F. Eder, H. Klauk, M. Halik, U. Zschieschang, G. Schmid, and C. Dehm, Appl. Phys. Lett. 84, 2673 (2004).

[5] P. F. Baude, D. A. Ender, M. A. Haase, T. W. Kelley, D. V. Muyres, and S. D. Theies, Appl. Phys. Lett. **82**, 3964 (2003).

[6] C. D. Sheraw, L. Zhou, J. R. Huang, D. J. Gundlach, T. N. Jackson, M. G. Kane, I. G. Hill, M. S. Hammond, J. Campi, B. K. Greening, J. Francl, and J. West, Appl. Phys. Lett. **80**, 1088 (2002).

[7] L. Zhou, S. Park, B. Bai, J. Sun, S. C. Wu, T. N. Jackson, S. Nelson, D. Freeman, Y. Hong, IEEE Electron Device Lett. **26**, 640 (2005).

[8] J. Collet, O. Tharaud, A. Chapoton, and D. Vuillaume, Appl. Phys. Lett. **76,** 1941 (2000).

[9] M. Halik et al., Nature **431**, 963 (2004).

[10] L. A. Majewski, R. Schroeder, and M. Grell, Adv. Mater. **17**, 192 (2005).

[11] J. Lee, J. H. Kim, and S. Im, Appl. Phys. Lett. **83**, 2689 (2003).