A review Paper: Ultra Low Cost RFID tags design using Organic Field Effect Transistor on plastic substrate

Prepared by:
Dileep Dhakal
Masters of Science in Nanomolecular Science

Submitted to:
Prof. Dr. Dietmar Knipp

Current Topics in Nanomolecular Science (420472)
Prof. Dr. Ulrich Kortz; Prof. Dr. Danilo Roccatano

2nd November 2009

School of Engineering and Sciences

ABSTRACT

I have studied the development of ultra-low cost printed Organic Field Effect Transistor (OFET) for RFID (Radio Frequency Identification), operating in high frequency (HF) range (13.56 MHz). For high frequency operation N/P type OFETs will have the mobility greater than 8 cm^2/Vs, channel length approx. 14µm and operating with supply voltage nearly 3V. The OFET will be developed on the plastic substrate which will practically eliminate fragile silicon wafer, which introduces flexibility in the integrated circuits. The OFET will dramatically revolutionize the current RFID market with all-printed continuous roll to roll and flexible printed circuits and individual tags, costing only few cents.

Fabrication an OFET on the plastic substrate will be performed in very low temperatures (lower than 100 °C) applying novel fabrication techniques. Nanoparticles rather than bulk conducting materials will be used as the interconnections for the RFID circuit development on the plastic surface. For very high mobility purest form of organic semiconductors (P or N type organic materials) will be created. Finally, passive components like inductors, capacitors and interconnections are also created on the same plastic wafer substrate to get the printed RFID circuit system.

.

PROBLEM STATEMENT

All-printed roll to roll electronics circuits fabrication can only be performed on the flexible materials like organic polymers esp. plastics, where any applied forces doesn't alter the electrical characteristics of the fabricated electronic devices like transistors and diodes. Very little technological advancement has been achieved yet related with polymer substrate fabrication because entire world is using Si based CMOS technology. Additionally, Plastic substrate technology also demands low temperature fabrication and current technology like e-beam lithography and vacuum processing cannot be applied. Hence, novel fabrication technology will be developed for circuit fabrication on plastic substrate.

Till today, OFETs have shown few promising properties required for the circuit application like organic FET based CMOS for basic logic inverter, suitable carrier mobility for proper output characteristics and larger switching speed, but still they exhibits major disadvantage, as very low carrier mobility. Despite the fact that, p-type OFETs have shown mobility nearly 10 cm^2/Vs, but unfortunately, n-type OFETS haven't crossed the 1 cm^2/Vs [1] [2] mark, which is rather discouraging but also a challenging task. Because, mobility of an organic material is an intrinsic property, which demands no costly fabrication processes but new organic materials can be generated by simple chemical reactions. Hence, novel organic material will be sought for and applied to create an organic CMOS for high frequency application. Low biasing OFET will only be realized of mobility goes higher or nano-transistors replace such organic FETS.

Fabricating passive components like capacitors, resistors and inductors on same plastic substrate too seems challenging because very few promising result on organic material based circuit components has been developed. Almost every available circuit components today are created using conventional Si based technology. Device performance of the circuit components on the plastic substrate also must be thoroughly studied.

INTRODUCTION

In recent days, lots of research in RFID for the item level tracking for individual consumer goods is being carried out. Currently available RFID systems can be categorized in three groups-Low end systems (LES), middle range systems (MES) and high end systems (HES) [3]. LES applies 135 KHz working frequency working in low range application esp. in Electronic Article Surveillance (EAS) having few memories 1Byte (Barcode information) found in shopping centres. Mid range systems have greater memory size (upto 100 KByte SRAM or EEPROM) that facilitates authentication between transponder and reader are found in Offices [3]. HES includes microprocessor and a co-processor system that operates in HF or UHF or Microwave frequency (MF) ranges are used esp. as smart card [3].

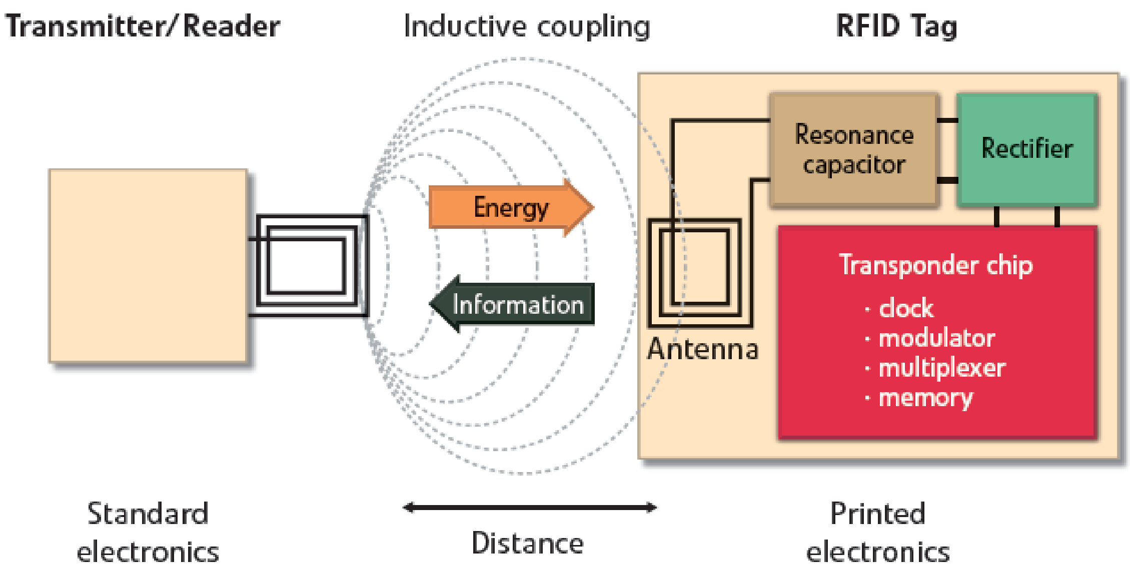


Fig. 1: Pictorial representation of the RFID system showing transmitter, the coupling section and RFID tag and application of printed electronics in RFID tag design [4].

Those devices ranging from 100 KHz to 30 MHz applies inductive coupling and operating in 2.45 to 5.8 GHz applies electromagnetic field coupling. OFET for operation in HF range (13.56 MHz) demands very low channel length ~14 μm for mobility of 10 cm^2/Vs and 1.1 μm for same mobility operating in microwave frequency (2.45 GHz). Equation below depicts the variation of MOSFET maximum switching frequency (f) along the channel with mobility (μ), gate voltage (V_{GS}) and channel length (L) as,

$$2\pi f = \frac{\mu \times (V_{GS} - V_{th})}{L^2} \qquad \text{.......... (1)}$$

The ratio of transconductance (g_m) to input capacitance (C_g) gives the measure of MOFET switching speed.

$$\frac{g_m}{C_g} = \frac{\mu}{L^2}(V_{GS} - V_{th}) \qquad \text{.......... (2)}$$

$$C_{ox} = \frac{C_g}{W \times L} \qquad \text{.......... (3)}$$

Where, V_{GS} is the gate voltage and V_{th} is the threshold voltage. Cox is the oxide capacitance and W is the channel width.

Today available RFID tads (Vicinity card transponder), operating in 13.56 MHz have very high cost ranging from 4$ - 5$ per tag, having storage facility of 2 K bit with size of 8.56mm × 54mm × 0.76mm [5]. Almost every available RFID tags today uses CMOS technology, fabricated on the silicon wafer substrate, with very high manufacturing cost. The cost can be dramatically reduced if the OFETs can be fabricated on plastic surface replacing the conventional Si-surface, eliminating older and expensive fabrication technologies like photolithography, e-beam lithography and vacuum processing with channel length less than 10µm.

Picture below depicts the basic structure of Organic transistors and diodes using semiconducting polymer.

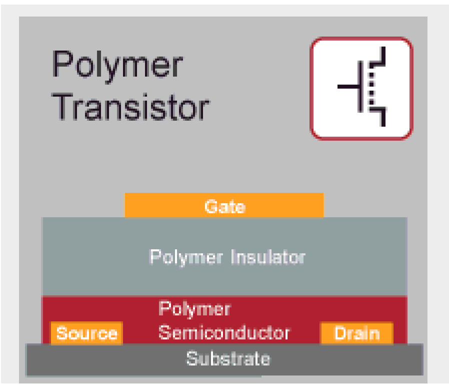


Fig. 2: Simple Top Gate Organic FET on plastic substrate, using semiconducting polymer which separates source and the drain, separated from the gate by the insulating polymer [4].

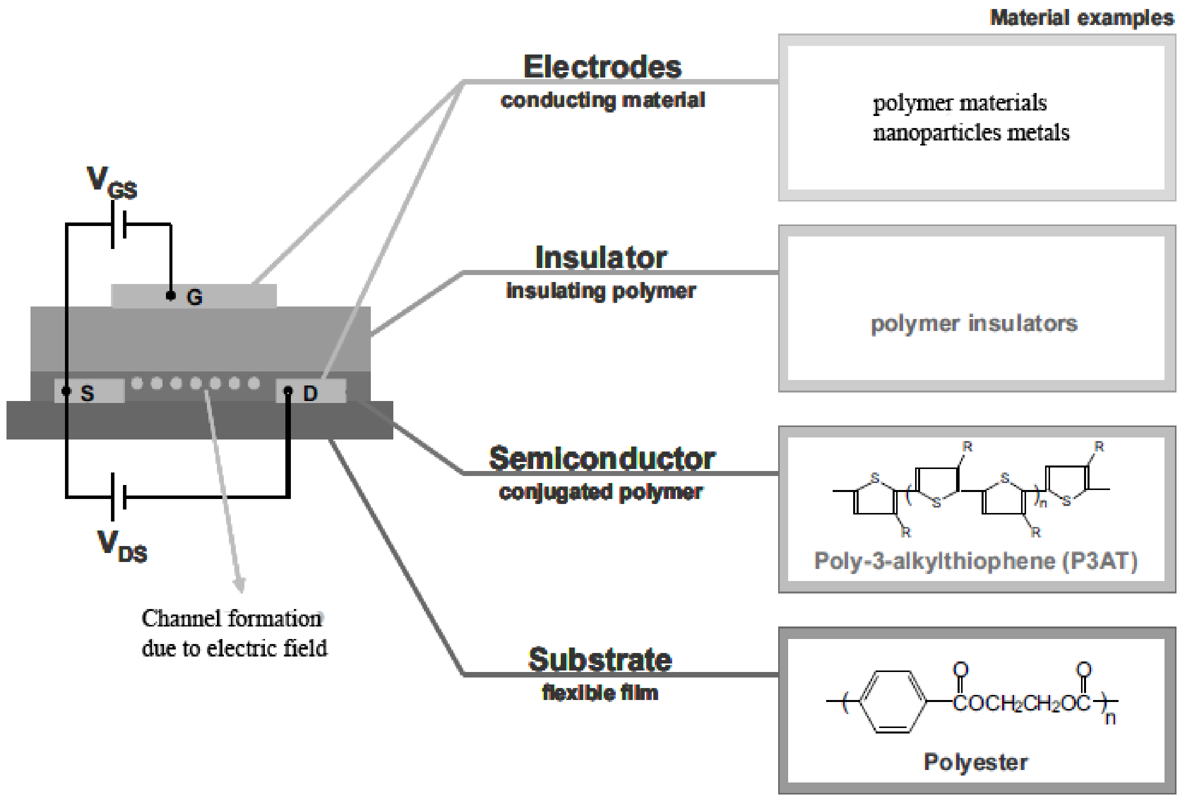


Fig. 3: OFET top gate structure based on organic polymers showing detail of suitable organic materials for fabricating a transistor [6]. S (Source), D (Drain) and G (G) are supplied with respective potential for the device to operate in forward biasing condition.

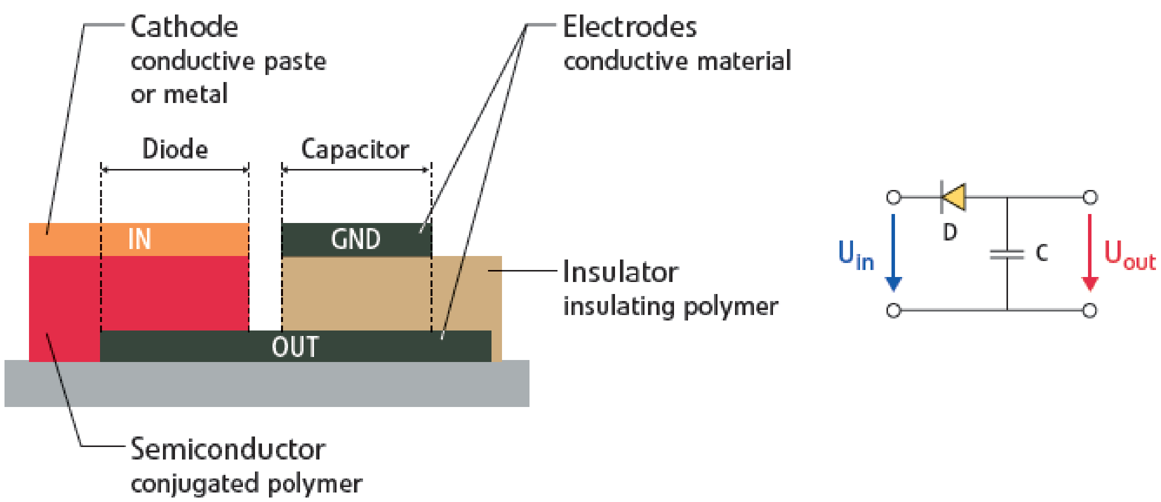


Fig. 4: Structure of a printed polymer rectifier (left) and the circuit diagram showing diode and capacitor [4] for RFID circuit (right). Conjugated polymer forms the semiconducting layer in the diode and insulator layer forms the dielectric layer for the capacitor respectively.

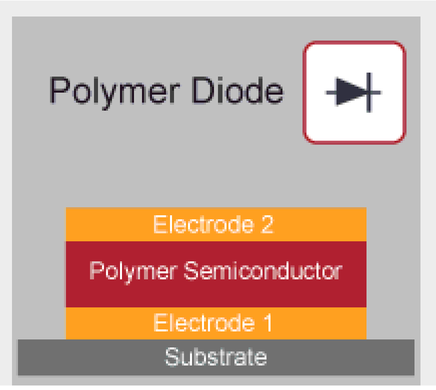


Fig. 5: Simple Organic Diode that uses semiconducting polymer between two electrodes [4].

Nano OFETs (channel length less than 100 nm) too can be applied in case of micro sized OFETs, which too can dramatically decrease the cost. But the major challenge involves is the elimination of vacuum sublimation process required for purification of highly volatile organic semiconductors. Vacuum sublimation process are necessary for organic semiconductor fabrication which results in highly ordered films, unfortunately this is an expensive methodology and cannot be applied to polymers because polymers tends to crack at high temperature [7]. Also, the plastic substrate have very low melting temperature thus, today available fabrication which requires temperature greater than 1000 °C, cannot be applied.

STATE OF THE ART

Extensive research in the field of polymer electronics was seen only in recent days after the Nobel Prize in year 2000 for Chemistry was awarded to Alan J. Heeger, Alan G. MacDiarmid und Hideki Shirakawa for their contribution towards polymer electronics for discovery and development of conductive polymers [8], which eventually initialized new era of printed electronics. Lots of companies started research and manufacturing of all printed electronics circuits and devices in following days. Epson announced the industry's first flexible 8-bit asynchronous microprocessor, in Frebruary 2005 [9]. Epson fabricated the microprocessor on a thin plastic substrate using low- temperature polysilicon thin-film transistors (LTPS TFTs), composed of 32,000 transistors, operating between 3.5 and 7.0 volts, and weighing only 140 milligrams, compared with other synchronous microprocessors; it consumed only 30% of the power [9]. PolyIC GmbH & Co. has already started developing flexible and printed RFID, using polymer transistor and diodes, called as electronic product code (EPC) tags [4].

Similarly, All printed and HF operating (13.56 MHz) first 4-bit RFID tags was developed in 2002, which also includes ring oscillator, antenna and integrated logic circuit [10]. Today, modern printing technology has reached resolution of 20 µm and more than 500m per minute which is equal to the production of entire silicon based wafer within an hour by using this continuous printing technology [6].

Pentacene-based thin-film integrated circuits powered by near-field coupling at radio frequencies of 125 kHz and above 6 MHz was demonstrated in 2003 [11], with carrier mobility of 1.5 cm^2/Vs at drain-source biasing of -40V. Due to its high mobility, Pentacene has attracted attention of scientists from all over the world [10] – [16], [28].

Many researchers around the globe had approached mobility upto 1cm^2/Vs using material in spin-cast films [12]. But RFID demands both n and p-type OFET with higher mobility, greater than 8 cm^2/Vs. Using vacuum sublimation method excellent performance OFET was realised using Pentacene material with carrier mobility greater than 10 cm^2/Vs [14], suitable for high frequency RFID application [16]. But vacuum sublimation process is very expensive procedures [10] which must be eliminated for the development of all printed flexible and ultra-low cost RFID tags.

Fabrication on plastic surface has also drawn attention of many scientists around the globe towards development of flexible electronic devices and circuit. Small diameters nano-particles (5nm or less) have reduced the melting point relative to their bulk particles has been observed, gold nano particles were found to have melting temperature less than 150 °C whereas bulk gold had melting temperature greater than 1000°C. [10] [17]. This property can be utilized in creating an interconnection within an electronic circuit on the plastic substrate, also can be applied for creating high quality factor (Q) passive components [19]. Same properties were also explored for Silver and Copper [20].

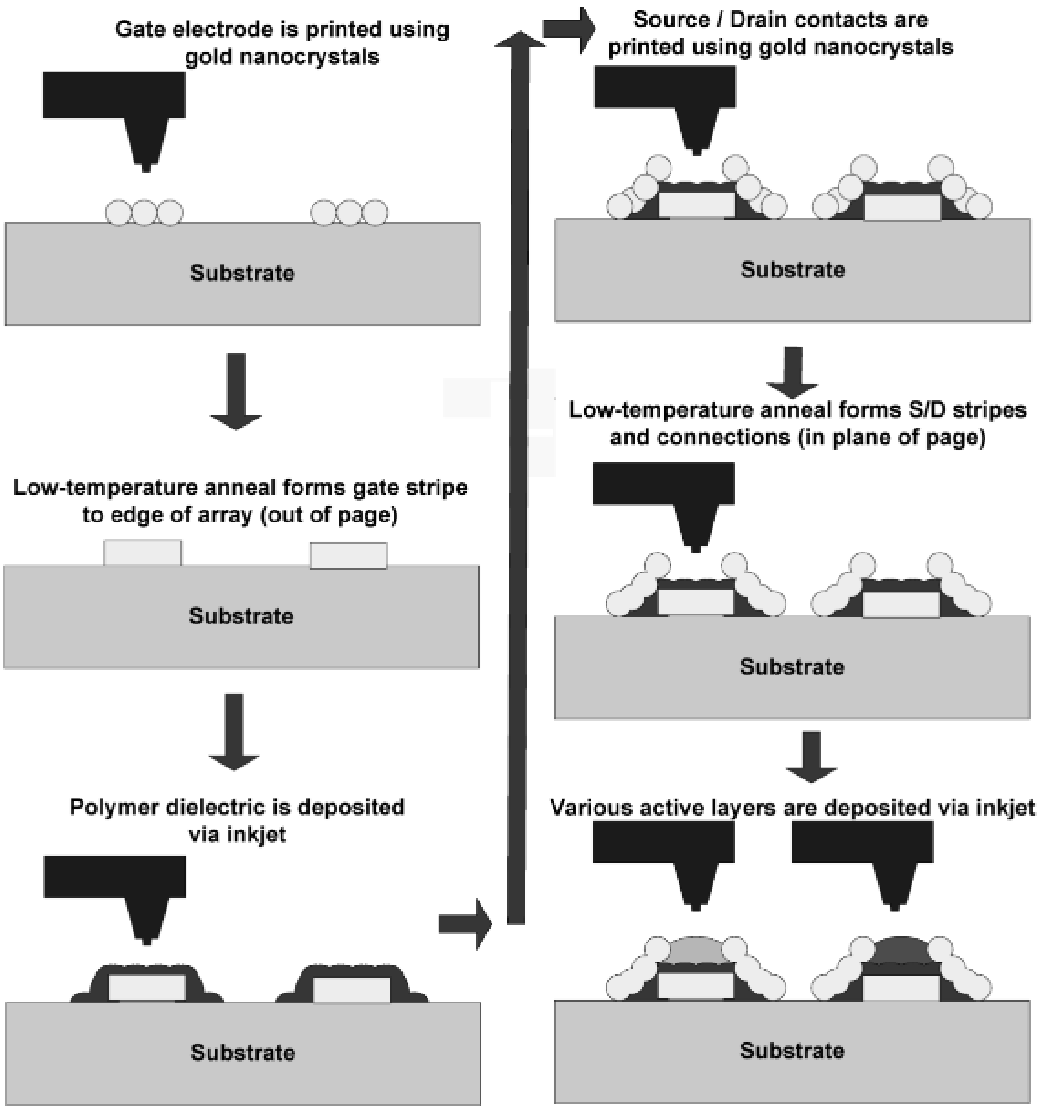


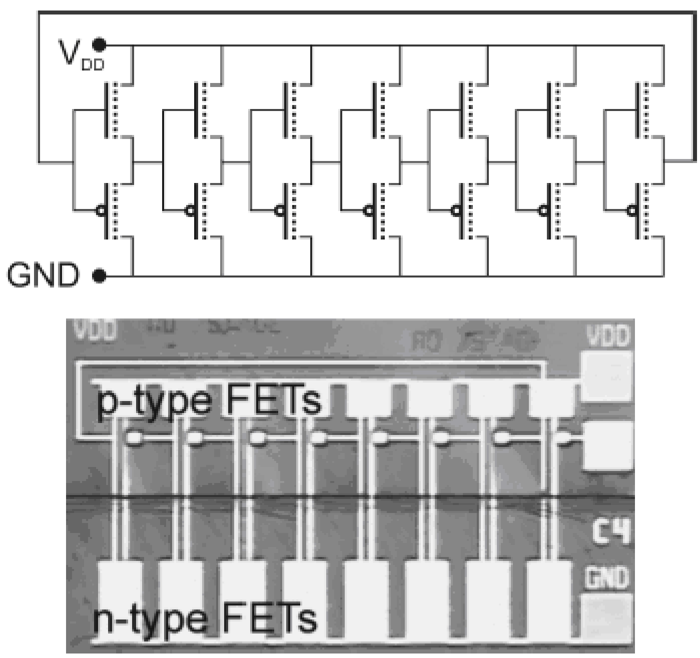
Fig. 6: Inkjet fabrication technology for low cost and low temperature fabrication [10] [19].

Applying the ink-jet printing technology many n- and p-type organic transistors had already been developed for fabrication temperature suitable for plastic substrate (less than 150 °C), and mobility of only 0.2 cm^2/Vs was found [17] for channel length greater than 10 µm [17].

For channel length 2 μm to 10 μm inkjetted devices were formed on gold pads, using single mono-layer inkjetted oligothiophene organic TFTs which gave mobility of 0.07 cm^2/Vs and ultra-low leakage currents [19].

Many printed circuit components today operates in very high voltage greater than 10V [10] [18] and also ring oscillators and inverters has been fabricated for supply voltage of 8.5V [21], necessary for the all-printed RFID circuits (Fig 1). Higher operating voltage is unacceptable for the RFID application; i.e. sub 4V operating transistors are necessary. Most of those devices used oxide thickness layer (100nm) [10]. Reducing the supply voltage to 3-4 V, oxide layer thickness can be reduced. Unfortunately, the reliable printing of thinner layer is difficult [10]. Scientists have developed alternative to the problem by applying self-assembled monolayer with operating voltage of only 2 V. Also, high K dielectric precursor has demonstrated sub 4V operation [10] [22].

Most of the researches on organic FETs had only explored the mobility for p-type material and development of p-type of OFETs, whereas very few promising results were found for n-type OFETs. A field effect transistor based on an n-type Dibenzothiophene derivative had produced mobility of only 1.75×10^{-6} cm^2/Vs [23]. Most of the fabricated nOFETs had poor stability with very low mobility ~0.01 cm^2/Vs [23] [10]. Using zinc-oxide Nanoparticles and sintering them like metallization have demonstrated slightly higher mobility around 0.1 cm^2/Vs [23].



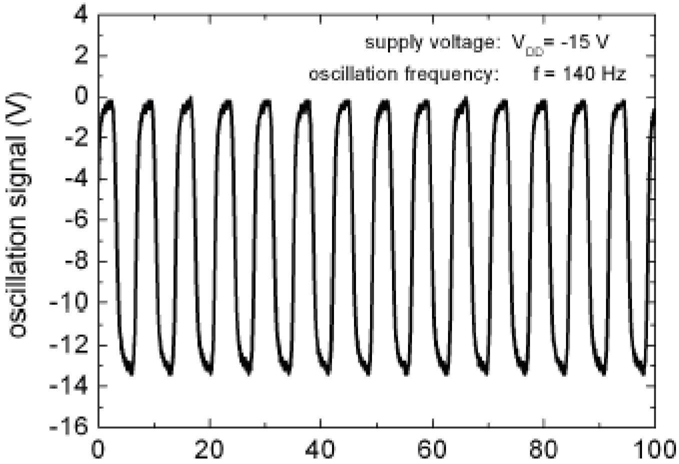


Fig. 7: Schematic diagram of 7-stage ring oscillator (top) and the fabricated structure (middle) and the device operating in 140 Hz with supply voltage of -15V (bottom) [6].

The complex logic circuit necessary for RFID implementation must have number of inverters [29] [27], which must show significant signal strength within the stages and the output signal of one stage must drive the subsequent stage (fig 7). This is tested by creating a ring oscillator. In 2003, a seven stage ring oscillator has been successfully tested, under following situations, first the circuit was tested at 85 °C under stressed condition for 85 hr and 85% humidity, and then circuit is dried at 60 °C for 3 hr, where only reduction of frequency from 56 KHz to 47 KHz was observed, with reduction of amplitude by only 10% [15]. In 2004, drastic improvement was seen in the operating frequency just by the improvement of material, which resulted in the increment of frequency to 192 KHz [24] and 0.6 MHz [24]. In 2005, Stijin De Stijin De Vusser, etal., has developed high performance OTFT operating at only 8.5 V, with output signal amplitude of 2V operating at a frequency of 15.8 KHz and with 15V at a frequency of 18.4 KHz and high frequency rectifier for 13.56 MHz A.C rectifier using pentacene as an organic semiconductors on glass substrate using SiO_2 as gate dielectric [26]. In 2007, A. Ullmann, etal., has developed the 64-bit RFID tag by combining many sub-circuits, operating with supply of only 14V, where signal could travel upto 3cm (inductive coupling) operating at 13.56 MHz frequency [25].

OBJECTIVES

This ultra-low cost will replace the barcode with electronic product identification codes (EPIC). Every single goods can be tagged using cheap RFID tags. These tags will have the facility to be read within the distance of 1m of vicinity.

Such tags will be printed in batch process, like those of newspapers. Millions of such tags can be printed within a single day. The RFID tags also houses memory unit, they can be used to store information about an individuals or the products. Memory within the device will differentiate the property of the tags and application of the tags. The flexibility property will make those EPIC tags universal used in the libraries, supermarkets as product tags and in the banks and research laboratories as security tags, for citizenships, passports and ID cards as identity tags. 1-bit tags can be used in the supermarkets while larger capacity can be used as identity tags. Processor embedded tags can be used as security tags. Also, cheaper tags can be used by the banks for printing the bank notes, which will stop contraband of the fake currency.

High frequency RFID tags operating in larger range can be used as intelligent product. Like the situation where a product which is capable of communicating with the reader- internet of products for a store, intelligent washing machines and refrigerators, intelligent shopping cards for the super markets and also automatic ID cards.

REFRENCES

[1] C. D. Dimitrakopoulos and D. J. Mascaro, '*Organic thin-film transistors. A review of recent advances*,' IBM Res. Dev., vol. 45, No.1, 11-27 (2001)

[2] S. K. Volkmann, S. E. Molesa, J. B Lee, B. A Mattis, A. de la Fuente Vornbrock, T Backhishev, and V- Subramanian, '*A novel transparent air-stable printable n-type semiconductor technology using ZnO nano-particle*,' in 2004 IEEE Int. Electron Device Meeting Tech. Dig., 769 (2004).

[3] K. Finkenzeller, '*RFID Handbook: Fundamentals and applications in contactless smart cards and identification'*, New York: Wiley (2003).

[4] Henning Rost, Wolfgang Mildner, '*On the way to printed electronics*', Kunststoffe International (2008).

[5] '*13-56 MHz Vicinity card Transponder*', http://www.robotshop.us/rfid-vicinity-card-transponder-1.html.

[6] Pro. Dr. Christof Wöll, '*Physical and Chemical Aspects of Organic Electronics- from fundamentals to functioning devices*', Wiley-VCH, 4-15 (2009).

[7] Ing. Enanvele Orgiv, '*Organic Thin film Transistors - An investigation of device properties, applications market perspectives*', Thesis, 15-17 (2007).

[8] *The Nobel Prize in Chemistry 2000*, http://nobelprize.org/nobel_prizes/chemistry/laureates/2000/

[9] John Boyd, '*EPSON takes major step towards flexible electronics*', http://www.epson.co.jp/e/newsroom/tech_news/tnl0505single.pdf, (2005).

[10] V. Subramanian, et al, '*Progress toward development of all-printed RFID tags: materials, processes and devices*', Proc. IEEE, Vol 93, 1330-1337 (2005).

[11] P. F Baude, D.A. Ender, M. A Hasse, T. W. Kelley, D. V. Muyres, S. D. Theiss, '*Pentacene based radio-frequency identification circuitry*', Appl. Phys. Lett. 82, 22 (2003).

[12] P. F. Baude, D. A. Ender, T. W Kelley, M. A. Hasse, D. V. Muyers, and S. D. Theses, '*Pentacene based RFID transponder circuitry'*, in Dev. Res. Conf. 2004, Digest, pp. 227-228 (2004).

[13] D. Knipp, R. A. Street, B. Krusor, J. Ho, '*Pentacene thin film transistors on inorganic dielectrics: Morphology, structural properties, and electronic transport*', J. Appl. Phys. Vol. 93 No.1, pp. 347-355 (2003).

[14] T.W Kelley, D V. Muyers, P.F. Baude, T. P. Smith and T. D. Jones, '*High Performance organic thin film transistors*,' in Proc. Materials Research Soc. Symp., vol. 771, PL6.5 (2003).

[15] A. Ullmann, W. Fix, H. Rost, and W. Clemens, '*Stability of polythiopene-based transistors and circuits*', J. Appl. Phys. 94, 2638 (2003).

[16] Hagen Klauk, '*Organic Electronics-Materials, Manufacturing and Applications*', Wiley-VCH, 1-50 (2006).

[17] D. Huang, F. Liao, S. Molesa, D. Redinger and V. Subramanian, '*Plastic-compatible low-resistance printable gold nanoparticle conductors for flexible electronics*', J. Electrochem. Soc., vol. 150, 412 (2003).

[18] Paul C. Chang, Steven E- Molesa, Ananda, R. Murphy, Jean M. J. Frechet and Vivek Subramanian, '*Organic Thin Film Transistors from a soluble oligothiophene derivative containing thermally removable solubilizing groups*', J. Am. Chem. Soc. 126, 1596-1597 (2004).

[19] V. Subramanian, et al, '*Inkjetted Passive Components on Plastic Substrate for RFID*', 2003 IEEE Device Research Conference, Conference Digest pp. 187-188 (2003).

[20] V. Subramanian, '*towards printed low-cost RFID tags: Device, materials and circuit technologies*,' Presented at the 2nd Advanced Technology Workshop on Printing an Intelligent Future. Printed Organic and Molecular Electronics Technologies, Boston, MA, 2003.

[21] Stijin De Vusser, Soeren Steudel, Kris Myny, Jin Genoe, Paul Heremans, '*High Performance Low Voltage Organic Thin Film Transistors*', Mater. Res. Soc. Symp. Proc. Vol. 870 E (2005).

[22] C. D. Dimitrakopoulos and S. Purushothaman, J. Kymissis, A. Callegari, J. M. Shaw, '*Low Voltage organic transistors on plastic comprising high dielectric constant gate insulators*,' Science, vol. 283, pp 822 (2005)

[23] D. Kolb, M. C Petty, M. R. Bryce, I. F. Perepichka, I. I. Perepichka, '*A field effect transistor based an n-type Dibenzothiophene derivative*', PHD Thesis (2006).

[24] W. Fix, et al., '*Fast and stable polymer electronic circuits*', edited by J. DeMaria, Symposium on Optical Science and Technology, No. 5217-01, SPIE, San Diego, CA (2003)

[25] A. Ullmann, R. Blache, A. Knobloch, W. Fix., '*CMOS circuits based on polymer semiconductors*', Proc. ICOE 2007, Eidnhoven (2007).

[26] S. Steudel, K. Myny, V. Arkhipov, C. Diebel, S. De Vusser, J. Genoe and P. Heremans, '*50Mhz rectifier based on an organic diode*', Nature Materials 4, 597 - 600 (2005).

[27] Qing Wu, Jingyi Zhang, Quinru Qiu, '*Design Considerations for Digital Circuits Using Organic Thin Film Transistors on a Flexible Substrate*', ISCAS 2006th Proceedings., 1270 (2006)

[28] P. F. Baude, D. A. Ender, T. W. Kelley, M. A. Hasse, D. V. Muyers, and S. D Theses, '*Pentacene based RFID transponder circuitry*', in Dev. Res. Conf. 2004, Digest, pp. 227-228 (2004).

[29] C. J. Drury, C. M. J. Mutsaers, C. M. Hart, M. Matters and D. M. deLeeuw, '*Low cost all-polymer integrated circuits*', Appl. Phys. Lett. 73, 108 (1998).