UNIVERSITY OF WATERLOO

Organic Radio Frequency Identification

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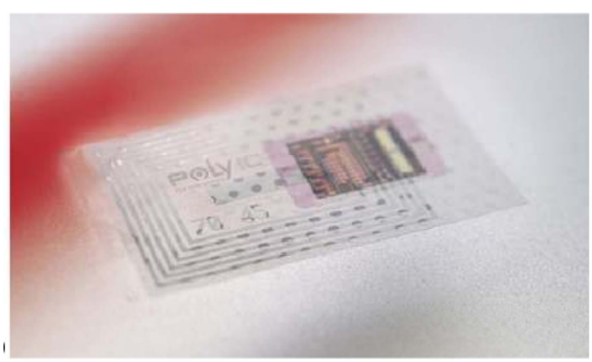

Abstract

Radio frequency identification (RFID) tags are devices that can be used to label products, or people, for the purpose of identification and tracking using radio waves. The idea is similar to bar codes, except RFIDs can carry more information, be reprogrammed, and can be read from long distances and by out of sight readers. An RFID tag is made of an antenna that receives the radio signal, a chip to rectify the signal and send out the identification data, and a reader that is used to send out the RF signal and receive the signal broadcast from the tag. Organic RFIDs (ORFIDs) are tags in which the chip is made from organic semiconductors rather than conventional silicon. The motivation behind developing ORFIDs is the potential for lower cost tags. Most silicon based RFIDs cost \$0.10-\$0.20, but this needs to reach at least \$0.01 for RFIDs to be used to tag individual items, which is only achievable with organics. This is because the manufacturing methods and materials for organics are lower cost than for silicon. Applications requiring such low cost tags include tagging consumer items for supply chain management and product authentication.

The key technical requirements of ORFIDs include the ability to operate at 13.56 MHz, have a long shelf life (two years or more), and be extremely low cost. The most popular organic semiconductor used in ORFIDs is pentacene. Typical deposition methods for such organics include vacuum deposition and solution based coating, with solution based being cheaper but producing lower quality materials. One of the main technical challenges is increasing the carrier mobility of pentacene and other organic semiconductors to allow operation at 13.56 MHz, without sacrificing shelf life and stability.

Many companies and academic institutes are actively researching ORFIDs. Currently, PolyIC is the only company to offer a commercial product. The market for ORFIDs is projected to grow rapidly. In 2009, it was worth \$5 million, and in 2018 it is project to be worth \$4 billion.

This report will give an overview of ORFID technology, discuss the key customer and technical requirements, investigate the current commercial outlook, and look at the most recent advances.

1.0 Background

1.1 Introduction

Organic RFIDs, or ORFIDs, are RFID (radio frequency identifier) tags made using organic components. ORFIDs operate similar to their regular RFID counterparts but with some important differences. There are no major changes in device operation, but the circuitry is completely different due to the incorporation of organics.

All RFID packages consist of 3 major components [1]:

1. The **antenna** of the RFID tag receives a broadcasted radio frequency (RF) signal from a reader. This RF signal induces a small AC current in the antenna through electromagnetic induction.
2. The **chip** in the RFID tag rectifies the AC signal received in the antenna and uses this power to charge a capacitor. This charged capacitor provides the power to operate the RFID. The chip ID and possibly other miscellaneous information is then sent out back to the reader through the antenna. The output signal is modulated in time by tag's unique ID.
3. The **reader** which sent the input signal now receives the new signal containing the ID of the chip with its own antenna through electromagnetic induction.

This report focuses on the chip component of the RFID package. The goal is to use organics to fabricate the chip instead of traditional silicon. The entire silicon circuitry within the RFID chip is therefore replaced with organic materials. Since organic CMOS has not been well developed at the time of writing, the circuit design of the RFID chip is quite different from conventional designs.

A large amount of research on ORFIDs started in 2004-2005 when the cost benefits of printing cheap organics on to a plastic substrate became apparent [2]. The organic molecule pentacene is the most popular organic molecule used in organic RFID fabrication [3]. Tetracene also holds promise, but pentacene is easier to process. Pentacene-based chips can simply be "printed" over the substrates using solution-based chemistry. The solution can then be evaporated by thermal annealing techniques.

1.2 Key Customer Requirements

The following key requirements need to be met by any organic RFID device to be considered practical for everyday application:

1. The ORFID must have a very fast switching speed, typically in the MHz range.

Currently, organic RFIDs operate at a much smaller frequency of 135 kHz [2]. However, very latest developments in ORFID research have demonstrated switching speeds of up to 13.56 MHz. 13.56 MHz is the desired frequency if being used individual item level tagging. This frequency has been designated for RFID tags. Higher frequencies, such as 900 MHz, are not ideal because they are affected by the material that the label is attached to, such as any metal or water that is inside the container. Lower frequencies, on the other hand, require significantly larger circuit components thereby making the device not only more bulky, but also more expensive to fabricate per unit. [1]

2. The ORFID must have a sufficiently-long shelf life

The ORFID must be able to withstand ambient moisture, humidity, temperature and UV conditions inside non-hospitable conditions like warehouses and garages. The device needs to be able to operate correctly for at least 2-3 years without any malfunctioning. If ORFIDs need to be replaced too frequently (< 2 years), they no longer become viable for item-level labeling. Pentacene molecules have a stability in the range of 1-2 years, usually 18 months [3]. Heavy research is being conducted in the field to increase the stability of pentacene [4]. Also, the threshold voltage of the device shifts slowly over time, and this too affects the lifetime of the device. A mere 20% shift in threshold voltage will alter the output power sufficiently to make the tag undetectable by the reader, rendering the RFID tag useless.

3. The ORFID must be extremely cheap and have a significantly low cost of fabrication

The unit cost of each RFID must be in the range of 1-2 cents in order to make it viable for large-scale item-level tagging and tracking in warehouses, airports, and freight services [1]. This low cost can only be achieved by means of an easy and cheap fabrication process known as "solution printing". This fabrication technique will be discussed in more detail in the following sections.

2.0 Technology/Applications Perspective

2.1 Barriers and Technological Advantages

The biggest technological barrier to organic RFID devices is carrier mobility [4]. The mobility of the carriers needs to be high enough to allow for sufficiently high switching speeds in the MHz range. The ideal switching speed is 13.56 MHz [5]. The operating frequency is therefore limited by the mobility of the carriers, and organic molecules typically show much lower mobility than silicon. It is therefore desirable to achieve high order and stacking (pi-pi) within organic-based circuitry. With increased stacking, more band splitting occurs and the band gap decreases, meaning more electrons can be found in the conduction band where unimpeded transport can occur.

The competitive advantage of ORFIDs is that ORFIDs use organics-based circuitry instead of a silicon-based circuitry, which results in huge cost savings. Silicon fabrication is cheap, but not as cheap as required for item level tagging. Currently, each silicon-based RFID tag costs around 10-20¢ at the very least. However, the cost needs to be as low as 1-2¢ if every item in say, a warehouse, was to be tagged. This low price can only be achieved with cheap organics that can be easily printed on to the substrate using extremely simple and cheap solution printing techniques. The low processing costs of organics results in organic RFID tags for as cheap as 1-2¢ per tag [1].

In addition to cheap processing costs, the initial investment for a silicon foundry is significantly higher than that of a low-cost organic printing facility [1]. Currently, the initial investment on a basic silicon foundry required to fabricate silicon-based RFID chip is about $3 billion. In contrast, the initial investment on a simple, organic printing facility is only $1-10 million: almost 300 times cheaper than its silicon counterpart.

Alternatives to ORFIDs, in addition to silicon-based RFIDs, exist. Paper-based traditional barcodes are the biggest competitor to organic RFIDs. However, paper-based barcodes cannot be used for real-time tracking applications since it requires human intervention to find the barcode on the item and make it face the reader directly. RFIDs do not have this limitation since all communication between the reader and the chip happens via electromagnetic waves in the radio frequency [5]. This eliminates the need for humans in the scanning and tracking stage and can therefore lead to further cost benefits down the line. Other alternatives are magnetic attachments used in retail stores to track pieces of clothing, for example. However, these attachments are bulky and are quite expensive.

2.2 Key Aspects of Technical Design

2.2.1 Materials

Organic RFIDs need to be made of an appropriate organic semiconductor material that is solution processable. The material must also have a sufficiently high mobility, typically more than 0.1 cm^2/V.s. Pentacene is one such material whose mobility is close to amorphous Si and has many processing options [3]. This material is commercially available and can be easily functionalized for solution printing. The structure of pentacene is shown in Figure 1. There are many other possible options such as Poly3-Hexylthiophene (P3HT) and Fluorene-co-Bithiophene (F8T2); these exhibit better stability but have lower mobility than pentacene.

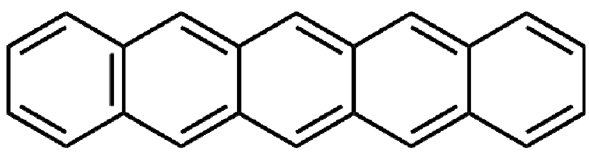

Figure 1. Molecular structure of pentacene [6]

The contacts need to be made of a material that minimizes source and drain contact resistance with the organic material chosen, i.e. pentacene, and should be printable. Viable contact materials are therefore PEDOT/PSS, PANI, and Au/Pt nanoparticles. The substrates can be made of polyester, polyimides and paper. The oxide layer separating the gate and the source and the drain can be made with simple plastics such as PMMA, PVP or other soluble inorganics.

2.2.2 Device Structure

The RFID comprises of an organic TFT (thin film transistor) for its active circuit components that typically has its gate at the back and contacts below the semiconductor layer since it is difficult to deposit and or pattern materials on top of organics [7]. Figure 2 shows a simple organic-based back-gate TFT device. Schottky junctions or diode connected OTFTs are used to make various other devices like rectifiers, ring oscillators and multiplexers. The channel length must be small enough to permit a relatively high frequency of 13.56 MHz, but very high resolution is difficult with printing processes [5]. It is also important to have a thin-enough oxide layer above the gate in order to maintain a low threshold voltage. Typically capacitors are also required for RFID operation, and are made using a metal-insulator-metal stack (MIM) using the materials mentioned in the previous section. A typical ORFID circuit design comprising these components is shown in Figure 3 below.

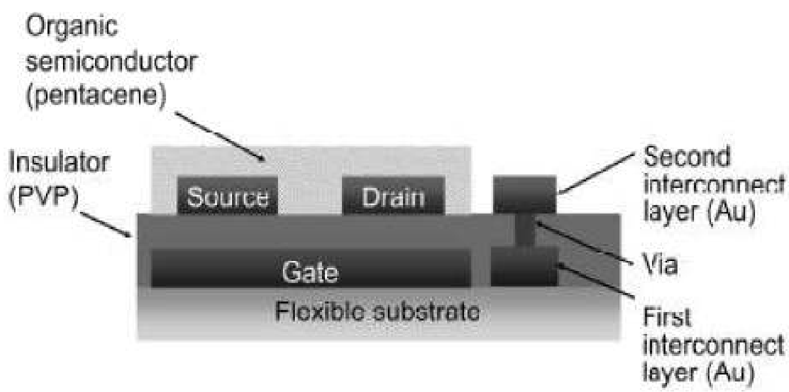

Figure 2. Back gate, bottom contact OTFT device structure [5]

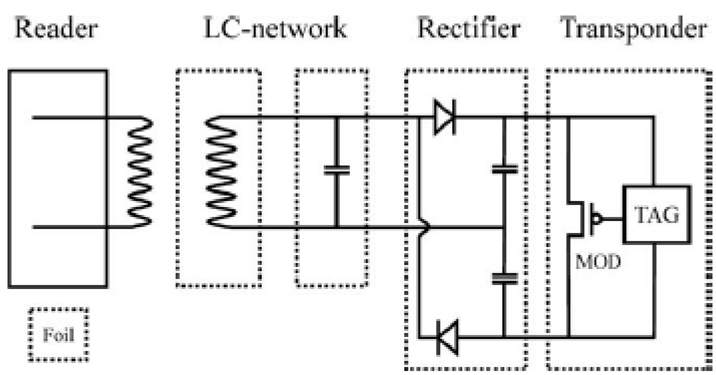

Figure 3. Circuit components and design of a typical ORFID [8]

2.2.3 Fabrication Processes

The two fabrication processes that will work for the large-scale fabrication of organic RFIDs are vacuum deposition and solution printing [1]. The fabrication process chosen needs to have a high yield and also low cost. Vacuum deposition will result in the highest mobility and purity, but unfortunately costs about the same as conventional silicon fabrication. It also has a low throughput for pentacene. Furthermore, it also requires a shadow mask for patterning [7]. Thus, vacuum deposition may be not as well suited for large-scale fabrication of ORFIDs. Solution printing can be achieved easily using inkjet printing which is cheap, but has a very poor resolution of only about 30-40 µm. Another solution printing technique is simple spin coating which is extremely cheap, but requires photolithography and the associated masks to pattern the device. Other techniques include gravure printing and flexographic printing. A common solution is to combine many different printing techniques into one manufacturing process [2]. This strategy seems to offer the best cost vs. complexity trade off.

2.3 Key Functional and Design Requirements and Specifications (Figures of Merit)

1. Operating Frequency

13.56 MHz is the desired frequency for item level tagging at medium distances. Higher frequencies, such as 900 MHz, are not ideal because they are affected by the material that the label is attached to, such as any metal or water that is inside the container. Lower frequencies, on the other hand, require significantly larger circuit components thereby making the device not only more bulky, but also more expensive to fabricate per unit.

2. Mobility

The mobility of the device is limited by the mobility of pentacene, the primary organic molecule in use within ORFIDs. The mobility of pentacene is currently in the 0.1-1 cm^2/V-s range [2]. Significant research is being conducted to enhance the mobility of pentacene and other materials for use in high-frequency applications such as ORFIDs.

3. Operating Voltage

The current operating voltage of ORFIDs is in the 10-20V range. In order to have long reading ranges, this high operating voltage will require power transmission above regulatory limits. Therefore the operating voltage should be within a 3-5V range. [4]

4. Cost

The cost of each RFID tag needs to be within a 1-2¢ range per tag to be feasible for item level tagging. This cost is still higher than that of barcodes, whose cost is essentially the price of paper, but RFIDs will have many more savings down the line since they do not require any human intervention to operate. A lot of the tracking processes can therefore be entirely automated, eliminating the need to pay wages to a human being.

3.0 Commercialization Outlook

3.1 Active Companies

The potential market for ORFIDs is very large, as the applications for ORFIDs are widespread across many industries. Therefore, many companies and academic institutes are actively researching ORFIDs, although almost no products are commercially available yet.

OrganicID was founded in 2003 and operates out of Colorado. They aim to develop processes to produce all required circuit components to build ORFID tags for between $0.01 and $0.05. In 2005 they announced one of the first organic RFIDs to operate at 13.56 MHz. In 2006 they were acquired by Weyerhaeuser, a paper and packaging giant, who are also working on ORFID development. [9]

ORFID Corp was a start up that was working to commercialize a vertical OFET based RFID. They are funded by Precision Dynamics, a California based manufacturer of healthcare and ID management products. They were targeting applications in the healthcare industry such as patient monitoring and asset tracking. However, since the time of the presentation, their website has been shut down. [10]

PolyIC is a company out of Germany that produces printed electronics. They offer RFID tags called PolyID, which are printed, so they are inexpensive, thin, and flexible, and appear to be made completely out of organic materials. PolyIC seems to be the only company that is offering a commercial product based on ORFIDs. [11]

Philips Research has published numerous papers on organic RFIDs, but do not have any product offerings in this area and have limited information on their website as to the state of this research. Finally, the Holst Center is a research lab conducting a large amount of ORFID research. It is an independent open-innovation R&D center funded by IMEC. In 2009 they announced a breakthrough 13.56 MHz ORFID, which will be discussed later. [12]

3.2 Potential Products and Applications

As mentioned, there are almost no ORFID products currently available to purchase. The most relevant is the PolyID from PolyIC. This product is an organic RFID that has a memory capacity of several bits, and has been used in areas such as trademark protection, authenticity control, sorting functions, and logistics. It is said to be roll to roll printed using polythiophene as the semiconductor, and printed on a flexible polyester film. They are mounted on an antenna and have a read range of about 1 meter. No information on the cost was available. [11] [13]

The applications for ORFID products such as PolyID are widespread. ORFIDs will be used in applications were cost is the key factor, not performance, since silicon RFIDs will likely remain dominant. Some cost-sensitive applications include individual tagging of consumer items for supply chain management (basically replacing the bar code), tagging for product authentication, smart cards for security, and tickets for events. Traditional Si RFIDs have seen only limited exposure to these applications because for wide spread adoption, the cost is currently too high.

3.3 Market Forecasts

The main driver for ORFIDs is cost reduction. The cheapest Si tags currently in the market are $0.20, and estimates predict Si will never reach $0.05 per tag. For item level tracking, the price needs to be $0.01 or less, which is where ORFIDs come in (Figure 4). [14]

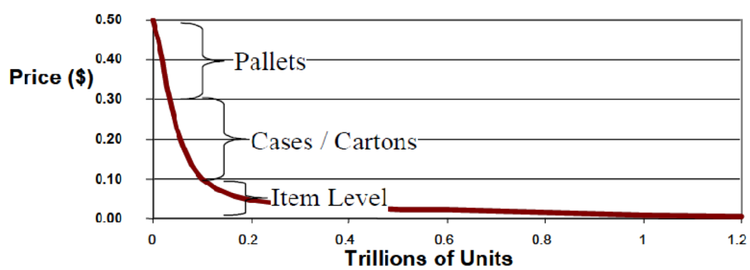

Figure 4. Price vs Number of Units required for RFIDs in various applications [14]

A recent report by NanoMarkets predicts printed RFIDs to generate $2.5 billion in revenues in 2011 [15]. NanoMarkets also predict that by 2015, 80% of organic electronic materials will be sold into RFIDs, display backplanes, and OLED lighting/displays. In 2015, RFIDs will account for US$6.9 Billion in materials sales. By 2012, it is predicted that ORFIDs will overtake OLEDs as the largest consumer of organic electronic materials. [16]

If ORFIDs can be produced at a cheap enough cost to replace bar codes, the market will be limitless. Over 5 billion bar codes are scanned daily, worldwide. MIT-Auto ID identifies 555 billion items to be individually tagged from their major partners alone, such as Walmart and Coca-Cola [17]. IDTechEx predicts that by 2018, the market for passive RFID tags, which is where ORFIDs fit, will reach over $10 billion (as shown in Figure 5). Of this, printed RFIDs are projected to take in $3.93 Billion. In 2009, the market for printed RFID tags sat at $5 million [18].

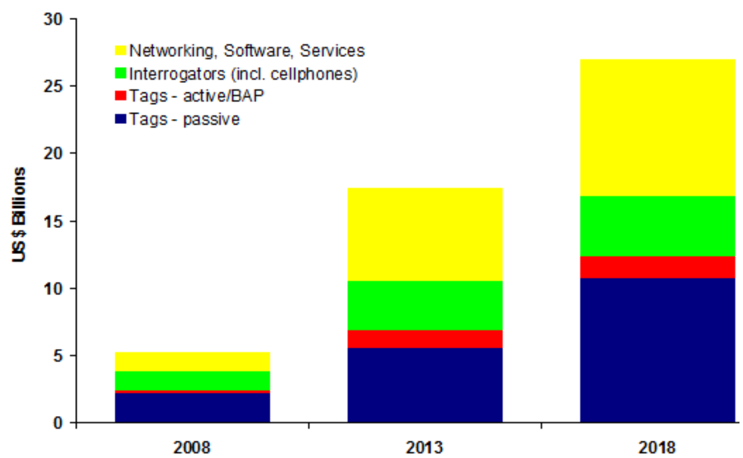

Figure 5. RFID market projections, 2008-2018 [19]

4.0 Recent Advances

The areas of focus in current research are on increasing the carrier mobility, lowering and stabilizing V_{th}, matching n- and p-type materials for CMOS implementation, increasing the number of bits and the bit transfer rate, and improving printing processes to achieve better resolution.

For p-type materials, the highest mobility reported for evaporated pentacene is 5.5 cm^2/Vs and 1.8 cm^2/Vs for solution processed pentacene [3]. This has been achieved by using side chains to control crystal nucleation and solution deposition parameters. State of the art side chains are based on silylethynyl, such as TIPS pentacene and TES-ADT (Figure 6) [20]. For n-type materials, one of the highest reported motilities is around 1 cm^2/Vs, which was achieved with a thiazolothiazole derivative fabricated on top of a self assembled monolayer [3].

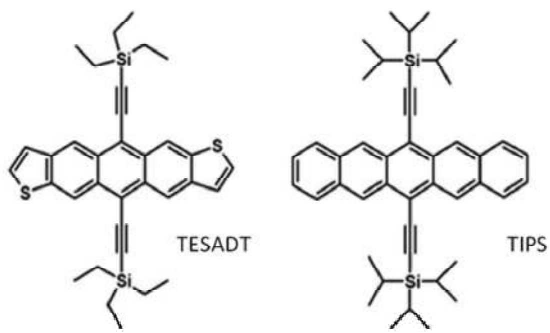

Figure 6. Two advanced p-type organic semiconductors [20]

Recent research has also investigated the incorporation of single-walled carbon nanotubes (CNTs) into polythiophene (PQT-12) semiconductors for increasing the mobility. TFTs made of this composite were ink jet printed and showed 7x higher mobility than pure PQT-12. [21]

In terms of device stability, p-type OTFTs (anthracene based) have shown to be stable for up to 15 months in ambient storage conditions, showing only a 20% mobility variation and a small increment in the on-off ratio. These devices were also stressed continuously 3000 times for V_{DS} +/-40V with no major variation in device parameters [3]. OTFTs made from n-type materials have not shown as remarkable stability due to the instability of the negatively charged radical anion on the semiconductor in the presence of O_2/H_2O, although some recent advances hold promise. A cyanated perylene carboxylic diimide derivative with an initial mobility of 0.12 cm^2/Vs degrades by about 1 order of magnitude over about 13 months in air [3].

In terms of complete ORFID devices, numerous state of the art devices operating at 13.56 MHz have been demonstrated. Perhaps the most recent and significant is that produced by the Holst Center last year (Figure 7). They produced 64 and 128-bit plastic transponder chips operating at 13.56 MHz. The substrate was polyethylene napthalate (PEN) foil, Au and Al were used for the contacts, parylene was used as the insulator, and pentacene was used as the organic semiconductor. Bit rates of 1.5 kb/s at a 24V supply voltage were demonstrated for the 128-bit device. The 128-bit device has over 1000 transistors on it. However it should be noted that some organic circuit elements were solution processed while others were made using vacuum evaporation. [8]

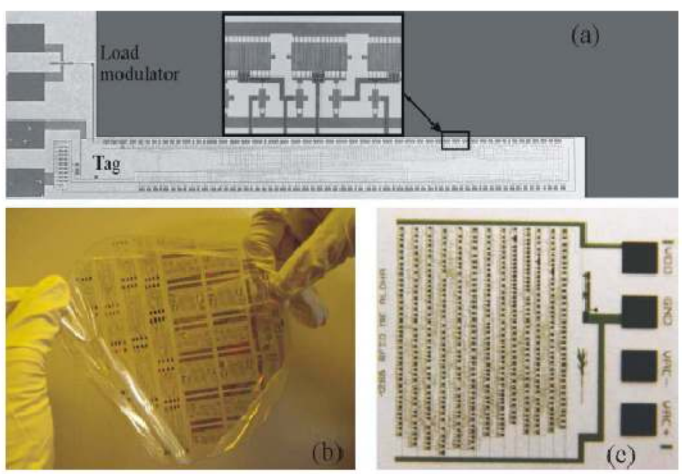

Figure 7. (a) 64-bit Tag, (b) 6'' wafer holding the transponder chips, and (c) 128-bit tag [8]

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