The Next Generation of RFID Technology

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Abstract The next generation of RFID will be governed by developments which have occurred in the production of printed semiconductors and in the manufacturing techniques by which RFID tags can be produced using these new materials. The paper considers all of these matters as well as protocols that are appropriate for printed tags.

1 Introduction

This chapter will be concerned with the future of RFID. In considering drivers of the future we observe that the world is never static. We take the view that RFID involves:

1. manufacturing,
2. technology,
3. protocols and
4. applications.

We conclude that in the future, RFID will involve a change in one or more of these items. Often a new development in one area will demand new developments in some others.

We have observed the emergence of printed electronics as a new development which we believe will have a significant impact on the future, and in this chapter pursue its implications in the area of manufacturing, and in each of the other three interrelated areas.

The future of RFID will see the traditional silicon integrated circuit with its complex and costly manufacture and antenna interconnect challenges gradually relegated to high-end tags requiring only the utmost operational performance in terms

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D.C. Ranasinghe et al. (eds.), *Unique Radio Innovation for the 21st Century*,
DOI 10.1007/978-3-642-03462-6_1, © Springer-Verlag Berlin Heidelberg 2010

of achievable reading distance, memory features and data capacity, speed of tag anti-collision arbitration and overall sophistication. Those supply chain market segments and other demanding applications are seen as remaining the exclusive province of traditional integrated circuit based tags.

EPCglobal UHF and HF Gen 2 (see http://www.epcglobalinc.org/standards/) are one example of an application space or area of the supply chain that will likely remain the domain of traditional and now complex albeit high performance single-crystal IC based tags. Alternative printed semiconductor based tags are not expected to significantly encroach on and compete in that space, but rather seen to flourish in the low and middle end applications where tag or label cost is the principal determinant and barrier to adoption, and where a pragmatic and judicious trade-off between cost and tag functionality is tolerable.

Fully printed RFID can potentially be one tenth or less of the cost to manufacture compared to the conventional silicon chip based tags (Frequently asked questions 2010). The target very high volume markets for printed tags include consumer product brand protection and authentication, disposable mass transit fare card ticketing, consumer retail product promotions, embedded product intelligence, etc. Many of these applications will capitalise on the eventual ubiquity of low cost readers, NFC technology and NFC enabled mobile phones and their wireless 3G internet connectivity, i.e. printed RFID manufacturers are going after the enormous market applications space where there is a good fit between the functional capability of the printed semiconductor technology and the end-use requirements; and importantly, which cannot ever be met by traditional IC based tag manufacturing methods. There are no “free lunches” however; simple low-cost fully printable RFID tags and labels come at a significant cost, complexity and functionality trade-off.

The imminent arrival of an alternative commercial printed semiconductor industry is nevertheless seen to open hitherto unachievable low cost points for RF labels and is expected to trigger large scale mass market adoption. This anticipated ubiquitous adoption has not happened with tags of cost constrained conventional single-crystal IC design and construction because of the RFID industry’s hitherto inability and failure to respond to and meet end user demand for truly low cost.

Printed electronics seeks to break the above nexus. The new and rapidly emerging field of printed electronics is an art of low cost semiconductor manufacturing which involves a combination of electronics and printing techniques. In recent years, there has been a significant level of interest in printed electronics since it is believed that it will realize substantially lower cost electronic systems than those available from conventional single crystal integrated circuit (IC) chip based circuit fabrication. Hence, printed electronics is often conceived as a feasible way to solve the high cost problem limiting widespread deployment of RFID tags through dropping the manufacturing cost per tag to the sub one cent level when processes and manufacturing plant is gradually up-scaled to high volume production. Manufacturers of printed RFID are projecting early selling prices of only a few cents in the billions of RFID labels and some foresee sub one cent pricing in much higher volumes.

Finally we can note that printed electronics is an enabling technology that also opens the future prospect for realizing integrated electronic article surveillance

(EAS) tags, i.e. labels with an added Electronic Product Code (EPC) or similar style product ID functionality. Enhanced performance 8.2 MHz EAS labels based on a high Q printed MOS capacitor element have also been demonstrated that, unlike conventional existing EAS labels, exhibit no Lazarus effect (tag function returns from the dead due to spontaneous healing of the capacitor dielectric layer) when cancelled with existing retail store EAS tag countertop infrastructure.

This chapter discusses in Sect. 2 the processes for low cost manufacturing in RFID. Section 3 makes comparison between organic and silicon ink printed technologies. In Sect. 4 printed semiconductor standards will be compared with those for single crystal semiconductors. Finally we present our conclusions on promising RFID technologies emerging in the 21st century.

2 Low Cost Tag Manufacturing

We commence this section by noting that costs for the kind of traditional IC based tags presently in volume production today have a significant assembly and ancillaries cost; e.g. in the chip attachment, and antenna manufacturing cost that collectively keep systemic tag costs high even if the IC chip component cost becomes vanishingly small. Additionally the cost of the tag substrate material is also a significant cost contributor, particularly for larger form factor tags. Future low cost manufacturing techniques and processes will need to address these presently limiting issues before significantly lower production costs of any circuit implementation can be commercially realized.

Currently, tag antenna manufacturing using material conserving additive processes such as printing electrically conductive inks or electroplating metals are estimated to make up less than 20% of the market today. Silver based inks are expensive, but newly developed metal nano-particle inks may show promise for lower cost. But that percentage is predicted to grow because printing antennas and selectively depositing conductors with plating processes offers significant cost savings over subtractive etching them from copper or aluminum clad laminate, which is the most common method of RFID antenna manufacture today. As a result of recent advances in materials science and nano-particle technology, ink design and printing processes, entire functional circuits and antenna can now be printed out of conductive and semiconductor polymer inks, which mean that entire RFID tags can now be printed.

Unlike the case with printed electronics RFID circuits, conventional CMOS IC based tag vendors can offer full-feature EPCglobal UHF Class I Generation 2 style tag functionality (particularly in the key areas of data security and high performance anti-collision protocols) with a small silicon die size that approaches the high speed mechanical handling limit for flip-chip naked die or strap or interposer style circuit attach. However, there are well understood and accepted asymptotic limits to the systemic manufacturing cost constraints of producing this kind of conventional non-printed RFID tags. Much of the mainstream tag manufacturing industry is today operating at or close to that limit; and the big manufacturers have practical strategies for scalable volume increases should market demand ever call for it. But that cost unfortunately does not downward scale with that volume up-scaling; that is the unique feature of printed electronics alone.

Regardless of the way in which the electronic circuit portion of the tag is implemented, manufacturers have hitherto failed to adequately address the holistic or systemic tag manufacturing costs in a demonstrable way. It is seen as a mistake to focus on one narrow aspect of the tag economics equation to the exclusion of these other factors.

We can introduce here the new nomenclature PIC, representing the acronym *Printed IC*. By way of representative example, the present PIC from printed electronics company Kovio Inc. is shown in Fig. 1.

This device has a long and thin aspect ratio form factor with electrical interface pads at each end with the structure designed to act as the crossover bridge for the HF antenna coil. This configuration eliminates the extra processing step and cost of printing a dielectric layer over the turns of the coil and subsequently laying down a conductive silver paste conductor to connect the antenna with the circuit pads.

Future RFID antenna manufacturing is likely to embrace large scale adoption of wide web continuous roll-to-roll additive processes based on the flash high speed electroplate deposition of copper onto polymer plastic or coated paper substrate materials on top of a direct digitally patterned seed layer. Such low cost antenna realization technologies have been in existence for several years but have not yet found widespread adoption against the backdrop of a hitherto constrained global demand for RFID labels, and where manufacturing volumes have not yet reached the sweet spot at which large economies kick-in with this process and provide compelling return on the plant capital investment.

Another recently developed very promising antenna mass production technology is based on wide web roll-to-roll high speed laser ablation/cutting of very low cost paper clad aluminum foil to fabricate HF and UHF antenna patterns. Although

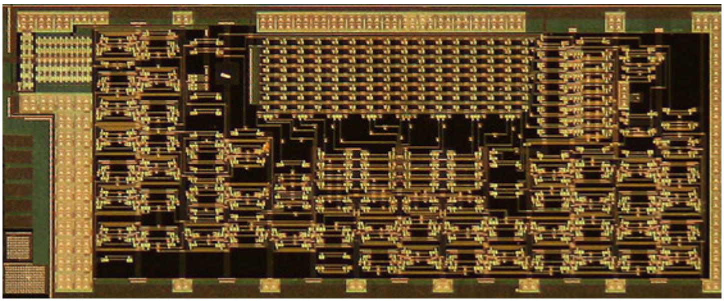

Fig. 1 Printed IC with circa 1000 TFT devices (Photograph courtesy of Kovio Inc. © Kovio Inc.)

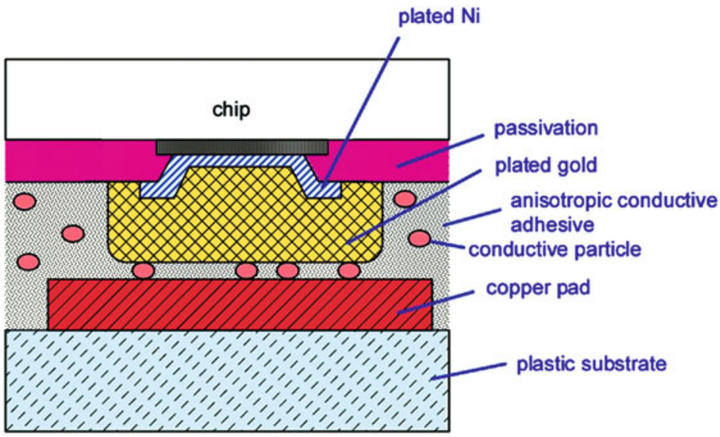

Fig. 2 Anisotropic Conductive Film (ACF) circuit attach

not an additive process, such metal clad foils are used in huge volumes in the consumer packaging industry and are very cheap raw material from which to fabricate antennas.

The Anisotropic Conductive Film (ACF) based thermosetting epoxy flip-chip IC bumped pad die or strap attach concept is shown in Fig. 2. This attachment method remains a major contributor of cost in today's mainstream tag manufacturing processes. Future low cost circuit attach techniques are likely to embrace electroplating bonding of the antenna metal directly to the IC or PIC pads. Such techniques have been shown to be commercially viable using substrate embossing and chip placement robotics. These kinds of new methods are likely to find commercial utility as future demand for very high volume low cost labels comes about.

As discussed above, there has been a significant level of interest by manufacturers in producing electronic devices through the use of a variety of printing processes. This has been to achieve substantially lower cost for realising mass produced electronic systems than can be achieved by conventional single crystal IC based fabrication. Such printing is expected to allow for the production of logic and analog circuit elements on flexible low-cost substrates such as paper, plastic and metal foils. Semiconductor circuit printing techniques potentially enable low manufacturing cost because of the greatly simplified process steps, low raw materials cost, and relatively small capital investment in the manufacturing facilities compared to a modern CMOS semiconductor fabrication plant. A comparison between conventional electronics and the printed electronics in terms of manufacturing process and costs is shown in Table 1.

As a result, printed electronics is considered to be the feasible way to solve the high tag cost problem in the RFID industry and to drop the cost per tag to one cent. However, currently and in the long term, the performance (possible operating frequencies) and compactness (number of transistors achievable) of printed electronics are much lower than those of conventional electronics. Therefore, the potential of

Table 1 Comparison between conventional electronics and printed electronics

	Conventional electronics	Printed electronics
Factory investment (Capital expenditure)	Very high for clean room and plant facilities (costing several 100s of million dollars)	No special needs
Processing	Photo-lithography etching based processing (complex processing steps)	Additive processing (simple processing steps, low raw material cost)
Substrate	Silicon wafer (many steps involved in preparation, high raw material cost)	Plastic, paper or metal foil (allows low-cost roll to roll or sheet feed processing

low cost of printed electronics can be realized only if it is achieved at an acceptable performance and compactness. These two features of performance and compactness are related to the combination of printing techniques and the printed electronic technologies applied.

In particular, the functionality and performance of an electronic circuit depends on the performance of each transistor composing the circuit and the number of these transistors, i.e. the circuit complexity. To enhance the performance of each transistor, the mobility of the charge carriers in the transistors should be maximized and the channel length between the drain and source of the transistors should be minimized. For organic printed electronics, the mobility is negatively related to the viscosity of the printed ink and for all printed electrics the achievable channel length is defined by the resolution of the adopted printing techniques (Sirringhaus et al. 2006; Knobloch et al. 2004; OE-A Roadmap for Organic and Printed Electronics 2009).

Furthermore, the resolution or minimum feature size also decides the circuit complexity. It is an application consideration rather than a technical issue because although you can have as many printed transistor integrated in the circuit as you want to increase the circuit functional-complexity, if the resolution is too low, the size of each transistor and also that of the complex printed circuit will be too big to implement in many applications.

Additionally, Subramanian (Sirringhaus 2009) concludes that the current throughput of organic printed electronics is still very poor which makes the cost of each printed transistor too high. Given the current large size and high cost per printed transistor, the printing technique is one of the key issues to fabricate a low cost RFID tag at an acceptably functional complexity and compact size. Therefore, it is worthwhile investigating further the printing techniques used in the fabrication of printed electronic systems.

Principally there are three kinds of printing techniques currently used in the fabrication of electronics:

Table 2 Printing techniques currently used for fabricating electronics

	Screen printing	Inkjet printing	Gravure printing
Ink Viscosity requirement	High (>1000 cP)[a]	Low (1–30 cP)[a]	Medium(40–200 cP)[a]
Throughput	Fast	Somewhat slower	Fast
Resolution	50 μm (commercial) 10 μm (laboratory)	< 20 μm	< 20 μm (commercial)

1. screen printing,
2. inkjet printing and
3. gravure printing.

Their features in terms of throughput, resolution and the requirement of the printing materials' viscosity are summarized in Table 2.

According to Table 2, the best of the achievable resolution in high speed screen printing techniques today is worse than 10 μm (Subramanian et al. 2008). Hence, the minimum channel length is about 10 μm which is several orders of magnitude less than that achieved by photo lithography based single crystal electronics (Sirringhaus et al. 2006). The low resolution of printed electronics leads to both substantially low performance (mobility and capacitance related) and compactness compared to the single crystal electronics just mentioned. Furthermore, in terms of material rheology and viscosity, for screen printing techniques in which the ink is pressed through a pattern screen on the substrate, an ink with high viscosity is required to prevent excessive spreading and bleedout (Subramanian et al. 2008). The required high viscosity inks are obtained by mixing polymer binders to the ink which degrades the mobility of printed transistors and the conductivity of conductors.

However, the manufacturing advantage of the screen printing technique is its high throughput. Conversely, slower inkjet printing meets the requirement of binder free low ink viscosity as shown in Table 2, but as a result of the low viscosity, the inkjet printing technique also suffers from drop to drop processing and drying phenomena and surface aberrations, line morphology variation, which factors impact upon the thin film deposition quality and the consequent tight control to attain high yield TFT devices slows throughput. However, the inkjet printing technique is widely used in both organic printed electronics and printed silicon ink electronics. Commercial printed silicon ink semiconductor developers are using highly customised inkjet print head delivery systems for applying their proprietary nano-particle formulation and solvent based ink technology.

Much cooperative research and joint product development effort is being undertaken by leading industrial MEMS based inkjet head technology vendors to address the demanding resolution and throughput requirements of the emerging printed semiconductor industry. Silicon ink developers like Kovio use high resolution inkjet printing of nano-crystalline compositions containing precursors to silicon, or germanium, metals and/or dielectrics to form TFT semiconductor channel, source drains and gates, conductor and/or oxide dielectric features to create their high carrier mobility CMOS printed ICs (PIC) with 10 μm design rules.

Reaching the goal of printing a few thousand TFT transistors per chip very cheaply requires an ability to deposit high-performance silicon inks quickly. Rather than focusing on the number of transistors per square centimeter, a key parameter metric in printed electronics is "how much material can be laid down in one place per second. Once you get the basic performance capability printed silicon ink technology has now achieved, it is all about how to do it faster. The primary goal going forward is to deposit more material very, very cheaply, instead of how small can you get the piece of silicon; the principal driver for the conventional single-crystal industry.

The gravure printing can simply be conducted between two rollers. One is etched or engraved with the pattern and loaded with ink, the other one is smooth. Once the substrate passes through these two rollers, the pattern is printed on it. This printing technique has drawn people's attention in printed electronics recently because of its high-throughput and relative low requirement on ink's viscosity (Sirringhaus et al. 2006; Subramanian et al. 2008). The disadvantage of this printing technique is its significant rate of defects which impacts upon circuit yield. It is reported that this printing technique has not been used in electronic fabrication yet (Sirringhaus et al. 2006; Subramanian et al. 2008).

As analyzed above, two conclusions can be drawn in this section:

1. The resolution of printed electronics is several orders lower than that of conventional electronics. This great divide makes the achievement of printed circuit with complex functionality within a tiny area impossible in the foreseeable future. The influence that the low functional-complexity of printed RFID tags has had upon current standards and protocols is discussed in Sect. 4.
2. The reason why researchers dedicate resources to research in printed electronics or in particular printed RFID tags is because its potential ability in lowering tag costs at a relatively acceptable functional complexity. However, as analyzed above, the realization of this expectation is highly constrained by the printing techniques, and research continues.

Besides the printing techniques, the semiconductor material technology of the printing electronics (organic or silicon printed electronics) applied is also critical to accomplish the expectation of adequate functional complexity at acceptable cost. Therefore, these two distinct branches or categories of printed electronics are investigated in Sect. 3.

3 Comparison Between Organic and Silicon Ink Printed Electronics

This section will also include some comparison with conventional integrated circuit electronics based on single crystal materials.

Organic and silicon printed ink electronics both adopt printing techniques in manufacturing but differ in the printed material (ink). The advantages and disadvantages of these two categories of printed electronic technologies, and their current development and applications, are discussed respectively in this section.

3.1 Organic Printed Electronics

Since the 1970s, certain organic materials attracted attention because of their conducting or semi-conducting properties. The researchers Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa then led the research and for their work won the Nobel Prize for Chemistry in 2000 (Knobloch et al. 2004).

More recently, interest in the semi-conductive properties of some organic materials, usually solution-processed molecular or conjugated polymer (Sirringhaus 2009) has continued and such materials have been deployed in various applications. Firstly, organic semiconductors can be made into diodes which can emit light. They can be processed to become displays, so called OLED (organic light emitting diodes) (Sirringhaus et al. 1998) displays. OLED displays are mostly on glass substrate and not printed yet (Das 2007). Conversely, they can also absorb light and transform the light into energy and therefore be used in organic photovoltaic cells, which is abbreviated as OPV. Secondly, various types of sensors can be made of organic materials (Crone et al. 2001; Liao et al. 2005; Someya et al. 2004). Last but not least, the organic semiconductor materials can be made into thin-film transistors (TFT) which have the ability to perform logic and analog circuit operations.

These printed thin film organic transistors (OTFT) can be integrated into RFID circuits (Chan et al. 2005; Steudel et al. 2006; Subramanian et al. 2005), and used as a basis of so-called organic printed tags. In the following paragraphs, the advantages and disadvantages of the organic printed electronics using in RFID are discussed and the current development of organic printed electronics in RFID industry are introduced.

As one type of the printed electronic technologies, organic printed electronics possesses the benefits of low manufacturing costs based on the printing techniques introduced in Sect. 2. Besides those benefits and compared with silicon printed ink electronics, organic printed electronics come with some other advantages, discussed as follows.

Firstly and apparently, the printed organic tags are environmental friendly. All the constituent semiconductor materials based on pentacene polymer plastics can be absorbed benignly and naturally in landfill after their disposal. This is a merit, but as discussed later, can also be a demerit.

Secondly, manufacturing allows low temperature processing (below 150°C) which makes the organic semiconductors compatible with flexible polymer plastic substrates, such as polyethylene terephthalate (PET) or polyethylene naphthalate (PEN), which materials cannot sustain high temperature but have low or moderate cost (Sirringhaus 2009).

However, there are some serious limitations and disadvantages which impede the application of organic printed tags.

First of all, the charge carrier mobility of the printed organic transistors is very low, compared with printed silicon transistors and not surprisingly even lower when compared with conventional single-crystal transistors. As stated before, mobility is the basic material parameter governing transistor performance. It is defined as the ratio of drift current density to internal electric field. The mobility parameter is critical for electronic circuits for following two important reasons.

1. It affects the performance of rectifiers (OE-A Roadmap for Organic and Printed Electronics 2009; Steudel et al. 2005) .
2. It governs the transistor switching speed and hence the maximum clock frequency that can be achieved in a tag circuit.

Most of the organic electronic devices are made using *p-type* accumulation mode. The mobility of such printed transistors is only of the order of 1 cm^2/Vs (Sirringhaus 2009). By contrast, the electron mobility for crystal silicon in conventional semiconductor electronics at room temperature (300 K) is 1350 cm^2/Vs and the hole mobility is around 480 cm^2/Vs, whereas the best mobility that printed silicon ink based transistors can presently achieve is believed to be about 200 cm^2/Vs for *n-type*.

The desire to achieve high mobility in organic printed transistors based on *n-type* accumulation mode is attracting researchers into that area. However, the low electron affinity of most organic semiconductors (3.5–4 eV) makes the formulation of an electron accumulation layer at the commonly used SiO_2-organic semiconductor interface difficult. Hence, the choice of gate dielectric becomes critical (Chua et al. 2005). The low mobility constrains the organic printed tags to working at LF (125 kHz) and HF (13.56 MHz) and with very low communication data rates on the tag return link. The highest achievable frequency for a rectifier based on an experimental organic printed tag is about 50 MHz (Steudel et al. 2006. To our knowledge, organic printed tags working at UHF have not been reported yet.

Furthermore, in the discussion in terms of the merits of printed organic electronics, one is that organic materials are environmentally friendly. All these materials can be absorbed naturally. However, because of that, the current organic printed devices based on both *p-type* and *n-type* are very sensitive to oxygen and moisture in the atmosphere, with *n-type* organic compounds being the worst (DeLeeuw et al. 1997). The working ability of exposed *p-type* based organic printed devices is restricted to a few months before degradation sets in. This working period drops to a few hours or days for unencapsulated *n-type* printed devices. Organic semiconductors are inherently ephemeral and suffer electrical parameter and performance stability issues. Much intensive research is underway to address and solve these device longevity limitations. On the other hand this acute transistor sensitivity to vapours and gaseous materials in the ambient environs can be constructively exploited by using exposed TFT channels for realizing low cost integrated organic sensor elements for future smart labels. These applications include food spoilage detection and novel biosensors.

In common with their traditional single-crystal IC counterparts, printed organic transistor based tags face difficult encapsulation and packaging challenges for very low-cost markets.

There are a few companies dedicating their R & D and commercialization resources to the applications of organic printed RFID tags. One of the leading companies in this area is PolyIC. In 2007, the company presented the first organic printed RFID tag working at the high frequency range of 13.56 MHz with a simple circuit and certainly low functionality (OE-A Roadmap for Organic and Printed Electronics 2009). It is only supposed to be used for brand protection and ticketing. Organic printed tags working in the LF band was obtained before the achievement of HF band tags. However, because the LF antenna element size is relative larger than that of HF antenna, the LF band tags are not applied as widely as the HF band tags. Philips also reported that a 64-bit tag composed of 1940 transistors is obtained based on organic printed electronics. The tag's data rate is 150 bits per second (Cantatore et al. 2007). As will be seen in the next section, this figure is much lower than that achievable with printed silicon ink CMOS technology, wherein a tag communication data rate of 106 kbps is believed to be achievable.

Organic semiconductor tags currently require a large power supply operating voltage VDD of 14 V and higher due to the high threshold voltage of the OTFT devices. This characteristic relegates high power consumption organic TFT based tags to inductive coupled LF and HF systems and where the tags consequently exhibit a requirement for a high strength energizing field from the reader system.

The key electrical parameters of the TFT devices such as VGS gate threshold voltage, VDS breakdown voltage, and leakage currents drift substantially with time and cause substantial problems in organic circuit design and in achieving predictable and repeatable operation; might be OK for a few hand-selected research laboratory prototypes but no good whatsoever in the commercial mass production of high-yield and reliable printed circuits. This manufacturing batch and product life cycle variation places significant demands on electrical parameter tolerant circuit design.

3.2 Silicon Ink Printed Electronics

Silicon printed ink electronics is a rapidly emerging environmentally friendly green semiconductor technology and is based on a much newer research and commercialization program than organic printed electronics. Processed silicon nano-particles are usually used in the printed ink formulation. There are very few publications in this research area and certainly very few commercial players, currently exemplified by Kovio Inc. of Milpitas California. However, we believe inkjet printed silicon ink based full complementary *n-type* and *p-type* (CMOS TFT) technology has some comparative advantage in terms of achieving low cost tag fabrication at an acceptable tag performance in the foreseeable future compared with organic printed tags.

Kovio has developed an enabling silicon ink in conjunction with other ancillary inks that are sequentially deposited on thin metal-foil substrates measuring 300–400 mm on a side. After the ink is printed on the substrate, it forms silicon islands that are annealed to drive out the solvents, leaving a poly-silicon crystal film. In addition to the primary "enabling ink" for the process, the company also developed oxide inks for the gate dielectric, inks for in situ *n-type* and *p-type* dopants and high conductivity metal inks for contacts to the silicon and forming really good quality interconnects having excellent electro-migration immunity properties.

Besides the benefits obtained with printed technologies in terms of low cost, there are a few more very attractive advantages associated with silicon printed tags.

First and foremost, the mobility in printed transistors based on silicon nanoparticles is much higher (orders of magnitude) than that of printed organic transistors. For example, Kovio, one of the leading companies in the silicon printed electronics field of activity claim that their n-type products' mobility can reach as high as 200 cm^2/Vs compared with approximate 1 cm^2/Vs obtained by organic printed electronics. This high mobility is achieved by an inkjet printing process (Johnson 2007; Lammers 2007; O'Connor 2008). Resolution and achievable feature size from the company's inkjet printing process is 10 μm now with a near term roadmap to 4 μm. As stated before, electron mobility in silicon in conventional electronics at room temperature (300 K) is 1350 cm^2/Vs and the hole mobility is 480 cm^2/Vs. Clearly, today's silicon ink mobilities do not rival the single crystal mobilities, but improvement is expected, and most importantly the present day (January 2010) process dependent mobility of 80–200 cm^2/Vs is much better than that of the current organic printed electronics, which leads to a faster data rate and allows the tag rectifier working efficiently at 13.56 MHz and enabling synchronous protocols deriving internal tag circuit clocking from the energizing carrier. Rectification with printed silicon TFTs at UHF is feasible albeit at much lower efficiency with the current device feature sizes and associated parasitic capacitance. We can attribute the less than single crystal mobility to the fact that even after the laser polymerization of the ink jet deposited silicon inks to form the *n* and *p* material, the material is still polycrystalline.

The silicon ink technology approach produces transistors from polycrystalline silicon, which is laser-recrystallized amorphous silicon, typically with the gate on top of the channel ("top gate" technology). This technology allows the source and drain to be aligned with the gate and therefore gives lower overlap capacitances. It makes it possible to produce *p*MOS transistors just as well as *n*MOS transistors. The electron mobility in polycrystalline silicon is higher than in amorphous silicon and the much lower threshold voltage is stable during operation and facilitates low power supply voltage operation.

Secondly, the silicon ink material is not as sensitive as the organic materials to the atmosphere which enables the silicon ink printed tags to exhibit much better environmental and electrical parameter stability.

Thirdly, the substrate used in silicon ink printed electronics is metal foil, because of the heat generated by high temperature laser annealing and polymerization of the ink jet deposited or screen printed silicon inks. The price of the thin metal foil, typically stainless steel, presently used for the small area PIC substrate is substantially lower than that of plastic films used as the substrate in organic printed electronics. The cost of petroleum industry derived polymer films is highly related to the global commodity price of oil. Silicon ink devices and circuitry can be readily fabricated on either roll-to-roll or large sheet format printing equipment as illustrated in Fig. 3.

Kovio made the strategic decision to differentiate itself in the printed electronics space by putting more value on TFT device performance than on low-temperature processing. Their methods use higher temperature processing of the materials after printing; these can still work with a flexible substrate, but it must be a metal foil, rather than plastic.

Despite these benefits, silicon ink technology shares with organic transistor technology the disadvantages of limited transistor numbers, so there is still an impact and limitation on the complexity of protocols. Somewhere around 2000 transistors is believed to be the comfortable upper boundary zone for printed semiconductor tag circuits today; but that is arguably all that is needed for achieving useful tag functionality to satisfy many less demanding end-user requirements. It is a return to the original MIT Auto-ID Center concept and very well-founded roots for "minimalist architecture" ICs having simple, but adequate protocols that fit within a modest number of transistors; a fundamentally important precept for the commercially viable realization of truly low cost tags for the mass consumer markets. Somewhere along the EPC technology and product development evolutional pathway that important precept got lost and abandoned because the focus back then was on the traditional single-crystal IC and few folks anticipated the fully printed-CMOS semiconductor revolution that was on the near term horizon.

This situation will undoubtedly change with the industry having to come the full circle back to the simple license plate only RFID tag concept so wisely contemplated

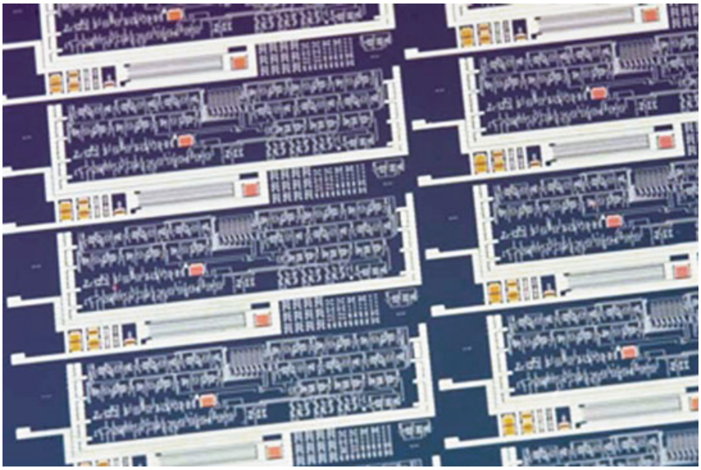

Fig. 3 PIC array in large sheet format (Photograph courtesy of Kovio Inc. © Kovio Inc.)

by the MIT Auto ID Center before the end user and technology vendor community bloated up the specification way beyond what is feasible for implementation with the then unforeseen low cost printed semiconductor technologies.

Silicon ink based tag memory today is based on either simple mask programmable ROM memory or OTP / WORM. Printed EEPROM memory cell structures, with their associated additional overhead of peripheral support circuitry, and with sufficient endurance and data retention time are down the commercialization roadmap for development and deployment in future generation printed tag products.

While printed silicon ink technology is well suited to implementing HF tags, it can also do UHF, but not at anywhere near the same long reading range traditionally associated with far field UHF tags of the conventional single-crystal kind. The reasons for this are threefold:

1. Rectifiers with the requisite high efficiency (RF input to DC output conversion) capable of operation at UHF are not yet possible or shown to be commercially practical with high yield printed semiconductor devices.
2. The VDD supply voltage needed to operate a printed silicon based TFT circuit is about two to three multiplies of today's single-crystal ICs due to significant differences in the printed transistor threshold voltages.
3. Higher circuit power consumption due to larger parasitic capacitances

These limitations mean printed silicon can do a UHF tag; but it will exhibit poor read range compared with established UHF products. The silicon ink technology could well do short-range proximity, near contact or few centimeter read UHF applications should a large commercial demand for low cost tags with that kind of operational characteristic emerge. On the other hand printed silicon could probably compete with near-field UHF tag systems should a significant demand for such tags take off some time in the future. This is because of the higher localized magnetic field strength / power density existing within the small volumetric confines of the true UHF near-field. This energy density is likely fortuitously conducive to overcoming to a useful extent the poor rectification efficiency and higher VDD and power requirements and hence the playing field somewhat leveled. However, this expectation would require empirical validation.

The relegation of printed silicon tag products to short range applications is viewed as not such a bad thing because having a small spatial volume of interrogation space also naturally limits the physical number of tags capable of being simultaneously in the field and thus greatly relaxes the anti-collision requirements to something that simple protocols such as Kovio and iPico (single-crystal counterpart with a simple *Tag Talks Only*, also called TTO, protocol) can deliver.

Whilst the above enumerated reasons also reduce the attainable read range of Kovio HF tags, vis a vis single-crystal HF tags, it is nowhere near as dramatic as with UHF. Hence printed TFT based tags are seen as much more competitive with applications for HF products.

Our conclusion after comparing organic and silicon ink printed electronics is that silicon ink printed tags are more likely than organic printed tags to replace conventional tags in many applications. This is because of their relative low price and high performance CMOS TFT circuitry that facilitate and supports fully synchronous HF protocols and fast communication data rates. Printed silicon ink technology can produce transistors that are fast enough for realizing high performance RFID tags.

We are not aware of any alternative high-performance based semiconductor enabling technology developments on the foreseeable horizon.

4 The Need for Printed Semi-conductors Standards as Opposed to Single Crystal Standards

Today's ISO/IEC 18000 EPC Gen2 specifications require circa 75,000–130,000 transistors to implement. That level of complexity is of course satisfactory for traditional semiconductor industry single-crystal IC chips, but is grossly incompatible and mutually exclusive for the now rapidly emerging new generation of very low cost fully printed RFID labels. An industry wide re-think is therefore necessary; and some new printed RFID centric and focused standards creation work is required if the piecemeal emergence of de facto standard(s) is to be averted. The now mature single-crystal standards were driven by the major stake holders of the global RFID technology vendors and semiconductor industry in response to perceived end user requirements. There is now a similar drive from end users in respect to standardizing low cost printed RFID.

The future challenge for the RFID industry is to develop in a considered and orderly manner some new standards based on minimalist protocols and tag architectures specifically targeted at printed TFT based semiconductor realizations. All of the technical standards in existence today have been designed around traditional single-crystal CMOS ICs where great complexity and large transistor counts is not a serious issue and can be tolerated without incurring significant penalty. However, the emergence of the printed CMOS semiconductor industry will bring a resurgence and urgent need to come the full circle back to minimalist principles based on simple, but efficacious system architectures. Such kinds of successful protocols have been exemplified by the iPico, EMarin, *Tag Talks First* (TTF) and TTO concepts and other published and unpublished proposals for simple *Reader Talk First* (RTF) terminating style protocols that are based on a limited command set. RTF protocols using a few very strategically chosen commands can be contemplated for use with printed tags, but doing so might arguably bring relatively few practical and operational advantages in many applications. The required tag State Machine digital logic can blow-out very quickly in transistor count whenever a reader command based protocol is adopted; even a modest one.

Although RFID has been strongly promoted for use in the supply chain (Cole and Engels 2006) we believe that emerging manufacturers of low cost RFID are planning to target the near term high volume markets of mass transit ticketing and rapidly emerging NFC applications, both of which have one tag in the interrogation field at a time. Low cost minimalist printed RFID HF label technology of the simple Tag Talks First (TTF), Tag Talks Only (TTO) "RF barcode" kind is attracting interest for deployment in brand authentication and protection, consumer product promotion, item level interactivity, asset management, event ticketing or wristbands, and retail loss prevention. Vendors of silicon ink based printed tags believe these highly cost sensitive markets will dwarf the size of the EPC market, so they are not currently very interested in taking on board the additional circuit complexity to address anti-collision issues and adaptive rounds. However, this chapter does mention those issues, which might become important in future applications, and might become practicable to implement as feasible transistor counts in printed technologies grow larger. However, protocols, anti-collision and security systems will still need a major paradigm change because of limitations on transistor count in printed tags. Until such time these protocol design and architectural aspects are simplified to only what is really necessary, the printed electronics industry is restricted from entering the supply chain EPC Item Level tagging market because of the yet to be addresses complexity issues. In the case of embracing fully printed electronics RFID labels the industry needs to experience an epiphany and associated shift towards minimalist thinking and low complexity performance oriented tag design.

4.1 A Simplified Adaptive Round Protocol

Many adaptive round protocols had been published for traditional single-crystal electronic implementation (Cole et al. 2002). But transistor counts are still outside the likely reach of printed electronic technologies. We believe that simplification of those protocols to eliminate such features as tag population selection and complex processes for detecting weakly replying tags, and exploiting deliberately limited tag operating dynamic range in the detection of collisions, could produce a simplified adaptive round protocol employing subcarrier modulation of four cycles in either the front half or back half of a bit period, and that this protocol might be achieved with about 2500 transistors. We believe that such a transistor count will become (or has become) commercially feasible in the near future.

4.2 An ISO Protocol

It is reported in (Harrop 2010) that Kovio have produced silicon ink based tags that adhere to the ubiquitous HF ISO/IEC 14443-A synchronous protocol, which has a return link data rate of 106 kbps. Bits are transmitted following the ISO/IEC 14443 Type A (Sect. 8.2) protocol specification, i.e. 106 kbps, Manchester encoding with

5% OOK (*on-off keying*) load modulation at 847 kHz. All the tag return-link parameters, subcarrier frequencies, modulation and data rates, etc are compliant with the published ISO specification. Notably, the Kovio tags use fully synchronous clocking which means they are easily read with traditional and existing 14443, 15693 HF reader equipment. The first generations of Kovio Printed IC (PIC) tags were designed to be a simplified sub-set of the ISO/IEC 14443A protocol; they did not implement any forward-link commands. The tags produced their 128 bit payload reply immediately on power up or power on reset and were TTO. The tags then continue to repeat transmissions after random sleep intervals for as long as they remain powered by the interrogation field and thereby facilitate a modest multiple tag read anti-collision capability. The associated absence of state machine logic and other peripheral circuitry to support commands allows a large reduction in transistor count down to approximately 1000. NFC reader hardware required minor firmware changes to accommodate the TTO communication protocol without the usual data flow control hand-shaking of the full protocol implementation. Significantly, the subcarrier frequencies and internal clocks are derived synchronously by direct countdown division of the 13.56 MHz interrogation carrier frequency. This clock synchronicity and very fast transmission data rate is something only high performance silicon-ink based TFT transistors and CMOS circuitry is currently capable of achieving.

Versions of printed silicon tags with this popular HF protocol have been demonstrated with NFC enabled mobile phone handsets and other standard legacy HF reader hardware. Leveraging on the installed reader and IT infrastructure and backward compatibility is foreseen as an important starting premise for any future printed electronics protocol standard. Perhaps all that might be required is a minor firmware upgrade change to read the simple PIC based labels. The reader infrastructure hardware or reader chip-sets including the latest embedded NFC readers remain the same.

Perhaps there are strong arguments in favour of adopting a printed electronics standards approach embracing and retaining core aspects, albeit simplified, of the ubiquitous 14443A HF protocol. The salient requirements being short proximity reading distance, modest anti-collision arbitration ability commensurate with a few cm distance and hence naturally self limiting number of tags simultaneously in the reader field.

4.3 The TOTAL Protocol

The ISO 18000-6(c) standard has a simple anti-collision protocol of about 50 tags/s (or maybe better) originating with IPICO (see http://www.ipico.com. The protocol being known as TOTAL – *Tag Only Talks After Listening*). This protocol, probably with the listen first aspect omitted, might be of interest to printed tag manufacturers when their interest moves from applications with single tags in the field to multiple tags in the field. Such a simple TTO protocol embodying just a few thousand transistors for its realization is deemed more than adequate for meeting many real-world applications. Tag architectural, protocol, and circuit implementation complexity is neither beneficial nor desired when contemplating a new printed electronics standard. This modified TTO approach is an exemplary example of a low transistor count protocol suitable for printed electronics, yet it still yields adequate fit-for-purpose performance for RFID applications.

Certain insightful and pragmatic sectors of the RFID industry today already understand this complexity / performance / cost trade-off and is a reason why the simple TTO protocols enjoy the popularity and support they do in retail item level and other applications. The TOTAL derivative of the simple TTO protocol has been integrated into ISO/IEC 18000-6 UHF standards revisions and update Committee Draft document being ratified by the SC31 technical subcommittee workgroup. The TTO or TOTAL protocol is based on an unslotted random hold-off and retransmission for tag collision arbitration, with a salient feature being no forward-link command transmissions emanating from the reader. Interoperability and non-interference with all other tags is achieved because a TOTAL tag, while powered, continually listens for the presence of reader modulation and only ever transmits its burst of randomised reply data in the absence of such modulated commands on an energizing carrier in its vicinity. Such quiescent stay-quiet operation inherently ensures the TTO tag never talks on top of an RTF tag such as EPCglobal UHF Gen2 (ISO/IEC 18000-6C) in mixed tag populations. One could argue such a talk after listening mode is not required for many restricted proximity distance HF applications.

5 Conclusions

RFID technologies based on microelectronic tags have made significant advances in terms of cost and performance. We have sought to acknowledge those developments and consider the next wave of technological advances expected to further drive the future growth of the industry through the reduction in cost of an RFID tag.

The road to realizing a really low cost tag has been identified: *fully printed tag including the antenna*. The realization of such a tag has been largely already solved by leading commercial players through low cost manufacturing techniques. Ink-jet printing is the outstanding example a simple low cost printing technique for realizing this vision. More significantly the technology has the capability for high volume production because it fully exercises the facility. However, what is needed is the requisite capital investment in plant to upscale and roll out “distributed” production facilities to match the upcoming demand expected in the following application areas.

- The EAS market because of the absence of the healing problem possessed by existing shortable capacitor labels.
- Potential application in the RFID area as security tags for anti-fraud and anti-counterfeit purposes.

- Disposable mass transit fare card ticketing.
- Most forms of near field communication (NFC) labels for the mobile phone based mass consumer space.

Based on various reasons outlined in the chapter the authors have sought to explore two key printing technologies suitable for printed tags: Organic Electronics and Silicon Ink Printed Electronics. There are a number of key issues that still needs to be solved prior to these technologies becoming a serious contender for single crystal silicon microelectronic tags. These issues are summarized in Table 3 below.

It is clear from Table 3 and our discussion that, for organic electronics technology to become a serious contender in the RFID application space there are significantly more hurdles to be overcome. Moreover, there does not appear to be clear solutions to the issues facing organic electronics in the near future. In contrast, the higher motilities supported by silicon ink printed technologies with support for both *n-type* and *p-type* transistors clearly offer a superior solution.

We see the clear need for a number of key developments outlined below to enable these emerging technologies to foray into the real world application space.

- In some application areas the present lack of an ISO/IEC air interface protocol standard that is specifically tailored and optimised to the requirements and transistor count limitation of printed TFT devices.
- The educational aspect of the need for end-users to appreciate the tremendous tag cost reduction opportunities if simpler less ambitious tag functionality were to be accepted and embraced.
- A requisite shift in mindset away from the entrenched architectural complexity of today's single-crystal products more towards simple "RF barcode" style labels of modest anti-collision capability.
- Solving a lightweight but efficacious and implementation compact data security mechanism.

Table 3 Key challenges and issues facing organic and printed silicon ink electronics

Silicon ink printed electronics	Organic electronics
Severely limited tag area for implementing security mechanisms in tags Need significant transistor numbers Assumption of only one tag in field made to keep protocols simple	
High temperature processing. Although this is not a serious impediment.	Only *p*-type can be fabricated while *n-type* is recognized as needed, but this does not appear to be in on the horizon. Low value for carrier mobility 1 cm^2/Vs now, with slow growth to 10 cm^2/Vs in 2016.

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