Exploration of Disruptive Technologies for low cost RFID Manufacturing

Badarinath Kommandur
M.S, Electrical Engineering, 1992
Arizona State University
B.E, Electronics Engineering, 1990
Bangalore University

SUBMITTED TO THE SYSTEM DESIGN AND MANAGEMENT PROGRAM IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN ENGINEERING AND MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2004

Signature of Author ....
Badarinath Kommandur
System Design and Management Program
March 31, 2004

Certified by ....
James M. Utterback
David J. McGrath jr. Professor of Management and Innovation
Thesis Supervisor

Accepted by ....
Tom Allen
Co-Director, LFM/SDM
Professor of Management and of Engineering Systems

Accepted by ....
David Simchi Levi
Co-Director, LFM/SDM
Professor of Civil and of Environmental Engineering and Engineering System

ABSTRACT

Significant developments have taken place in defining technology standards and identifying avenues for technological innovations to reduce the cost of manufacturing RFID tags below the $0.05 price point. The Auto-ID center at MIT has been the central coordinating body with participation from 5 universities and over 100 industry partners. The primary focus of these efforts has been in developing a standard which minimizes the logic capability of on chip circuitry and using radical innovations to reduce the cost of assembly of the RFID tags. Various disruptive innovations are underway to explore lithographic techniques which can reduce the cost of fabrication in the sub 100 nm regime wherein photolithography faces significant challenges.

This research analyzes the value chain in the RFID industry and reviews potential technology strategies using the double-helix model of business dynamics and Porter's five forces framework. It also explores the current state of the art in RFID tag manufacturing and proposes the application of disruptive technologies in conjunction with innovations in assembly and packaging to enable a low cost RFID system design. Five key emerging technologies which are examined in detail are Nanoimprint Lithography, Step and Flash Imprint Lithography, Inkjet Printing, Soft lithography and Spherical Integrated Circuit Processing. These are analyzed in terms of application to RFID tag manufacturing. Current innovations in high speed and low cost assembly and packaging techniques are also examined. Fluidic Self Assembly, Vibratory Assembly, Chip on Paper techniques are reviewed in terms of application to RFID manufacturing.

A systems thinking approach is also pursued to explore the drivers for wider acceptance of RFID based applications in addition to just depending on cost reduction for crossing the chasm from early adopters to a wider market penetration.

ACKNOWLEDGEMENTS

I would like to acknowledge the invaluable guidance provided by Professor James Utterback throughout the course of the thesis research. The critical analysis skills gained through the interactions with Professor Utterback in analyzing emerging technologies and to view them in terms of a broad scope of application rather than a narrow perspective will be critical to the author throughout his career in exploring emerging technologies for new applications. This learning started within the first month of joining the System Design and Management Program when the author had the opportunity to participate in the "Disruptive Technologies-Are you Predator or Prey?" class at Sloan School of Management at MIT.

I would like to express my appreciation to Reynold D'sa, my manager at Intel Corporation, for providing me with once in a lifetime opportunity to attend the System Design and Management Program as part of the Intel Scholar Program. In addition I am indebted to Sunil Shenoy, Brad Hoyt, Rani Borkar and Everardo Ruiz for providing me the encouragement and opportunity to pursue a full time academic rotation at MIT while being an Intel employee.

I have gained valuable insights through numerous class discussions with leading faculty at MIT and my fellow SDM classmates. In particular the valuable insights gained in discussions with Professor Carlile, Professor Fine, Professor Nicholas and Professor Sterman to name a few, provided an exceptional educational experience. The valuable discussions with Prithvi Bannerjee, Chris Lim, Sam Weinstein and Ion Freeman during the course of the SDM classes and projects added to a rich learning experience.

A special thanks to my six year old niece, Surya, who made sure that I kept up with my academic coursework every week by checking in with the question "Are you done with your homework?" and my five year old nephew, Rahul, who volunteered to help me with my thesis when he found out that all I had to do was lots of reading and writing. A very special note of appreciation for my wife, Shobana, who has been a tremendous source of support and encouragement during my academic program at MIT.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

While RFID technology has been used in a variety of applications over the last three decades, the holy grail of low cost manufacturing of RFID tags has prevented it from replacing the traditional bar codes used to identify items in the supply chain. RFID technology promises unique advantages of being able to uniquely identify each item, non-line of sight multiplexed readout and the capability of smart tags which can enable real time monitoring of environmental information in addition to inventory management.

Significant development has been undertaken by the Auto-ID center at Massachusetts Institute of Technology. Auto-ID center was a consortium of universities and companies working in close collaboration with the goal of defining standards and technology development to enable low cost RFID tags which can be deployed on a large scale as a potential replacement for bar codes. The Auto-ID center claims to have defined low cost manufacturing techniques using traditional semiconductor processing technologies with incremental innovations in packaging and assembly domains. Subsequently this center was closed in October 2003 and the standards definition task was undertaken by a non-profit organization-EPC Global.

The RFID tag architecture proposed by the Auto-ID center is based on a minimalist approach with the aim of minimizing the die size and cost of manufacturing. Since traditional semiconductor processes have been utilized which rely on expensive lithography techniques, this approach may not scale to further reduction in costs when the complexity of the tags is increased in the future to incorporate additional functionality in the tags.

1.2 Objectives

The telecom industry saw a loss in market capitalization of over $2 trillion during the last five years with the major players in the value chain reporting net losses over $60-70 billion. These include the telecom equipment manufacturers, systems suppliers, network operators and software companies. The current capacity utilization for optical fiber is less than 10% with an expected lifetime of 15-20 years. A simple system dynamics model to show the sources of the overcapacity is shown in Figure 1.

The current growth rates in internet traffic of around 20% will still take up to 5 years for capacity utilization to reach the installed capacity. The excess capacity and lack of killer applications requiring dramatic bandwidths has translated into downsizing in the telecom sector with elimination of over 170,000 jobs.

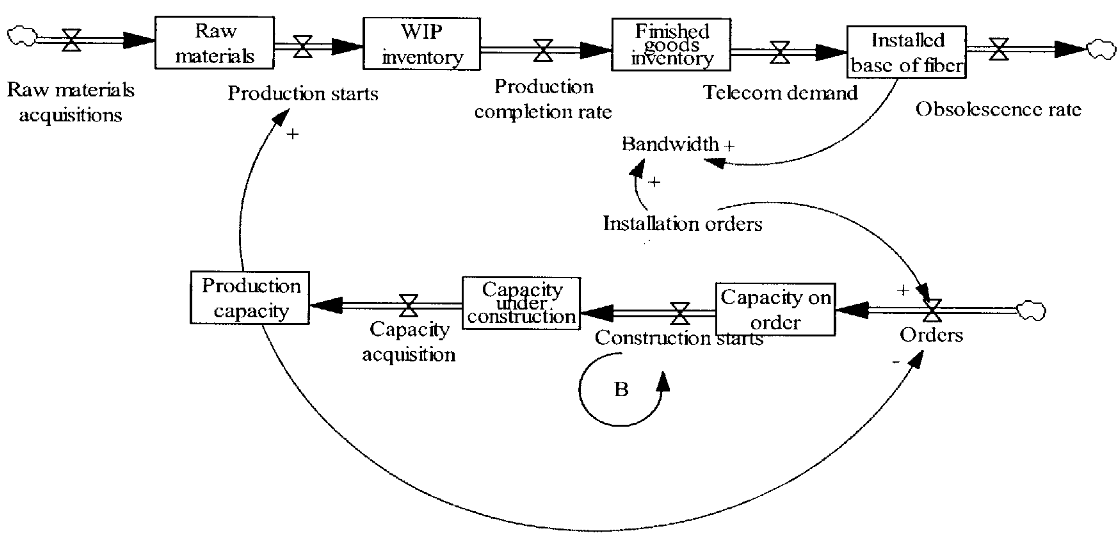

Figure 1 Sources of Fiber Overcapacity

With the recent announcement by major retail chains like Walmart and Target to switch to a RFID based supply chain inventory management system; there is a distinct possibility of major increase in bandwidth utilization in the communication infrastructure. In addition US Department of Defense has also issued a directive to require its major suppliers to start using RFID based systems for inventory management.[16] A major factor limiting widespread utilization of RFID based inventory management and other applications is the cost of manufacturing of RFID tags. Current estimates place the cost of passive tags at $0.25-$0.50. This is significantly more expensive than barcodes which it aims to replace for item level tagging.

This thesis aims at investigating alternative methods for the manufacture of RFID tags and its impact on widespread adoption of the RFID based systems for inventory management. Another area of research is the factors in addition to cost of tags which might limit wider adoption of the RFID based tracking systems. In particular, security and privacy concerns are investigated and current approaches to address these are examined.

An area of further analysis is the validity of the current approach in utilizing conventional semiconductor manufacturing techniques to reduce the cost of RFID tags and the constraint it places on minimizing the amount of logic contained in the RFID tags. An effort is also made to analyze the impact of addition of functionality in the RFID tags and the necessity of using emerging methods of semiconductor manufacturing and its impact on the organizational value chain.

This research looks at the technical constraint of implementing low cost RFID tags using conventional lithographic techniques and the cost drivers for the manufacture of the tags. In addition a systems perspective is used to understand the components of the architecture of the RFID tags and the issues which will need to be addressed before a wider adoption of the RFID based inventory management systems. An analysis is also made in comprehending the impact of technological innovation on the core competency of key members in the RFID value chain.

1.3 Approach

The primary starting point for this research will be the significant development work coordinated under the auspices of the Auto-ID center at MIT. Further research will be done through literature surveys in academic and business journals. In addition, interviews will be conducted with key technologists at Intel Corporation and faculty at MIT to forecast the future technological trends which may enable low cost manufacturing for smart RFID tags and readers. Industry value chain will be analyzed to explore competitive strategies for companies in different segments of the RFID industry.

1.4 Structure of Thesis

Chapter 1 provides an introduction to the motivation of the thesis research and outlines the focus areas for investigation. It identifies RFID based inventory management systems as one of the growth catalysts for the communication and computer industry.

Chapter 2 summarizes the results of the literature review to understand the applications of RFID systems. It provides a background into the benefits of RFID tags compared to barcodes for inventory management applications. In this chapter an overview of emerging semiconductor manufacturing techniques is presented which have the potential for cost reduction for RFID tag manufacturing.

Chapter 3 provides a technology overview of RFID systems based on inductive and electromagnetic coupling. A detailed review of application scenarios of RFID systems along with adoption timeline is detailed in this chapter. Classification of RFID tags along with a comparison of key performance metrics is presented.

Chapter 4 reviews the architectural decomposition of a RFID tag and discusses the future evolution of the tag architecture with respect to the integration of smart sensors. The traditional integrated circuit test and validation flow is explained to highlight the difficulty of adapting it for RFID systems.

Chapter 5 presents a value chain analysis for the RFID industry. The industry structure is analyzed in the context of the double helix model of business dynamics. The competitive strategy of different members in the value chain is also discussed within the framework of Porter's five forces model.

Chapter 6 presents a detailed review of five emerging manufacturing techniques which can be adapted to enable high throughput, low cost RFID tag manufacturing. Nanoimprint lithography, Step and flash imprint lithography, Inkjet printing and Spherical integrated circuit processing is discussed in detail.

Chapter 7 analyzes the barriers to using traditional packaging techniques for low cost, high volume RFID manufacturing. It reviews four recent innovations currently being used for low cost RFID tag assembly and packaging. Fluidic self assembly, Vibratory self assembly, Chip on paper and Parallel integrated circuit assembly is reviewed in this section.

Chapter 8 discusses the security and privacy concerns which need to be addressed even if we are able to overcome the cost barriers for RFID systems in order to enable wider adoption of RFID based inventory management systems.

Chapter 9 presents a conclusion of the thesis research with recommendations for future work. A comparison of the emerging technologies for semiconductor manufacturing using Christensen's framework of disruptive technologies is detailed in this chapter.

1.5 Chapter Summary

Chapter 1 provides the motivation of this research in exploring constraining factors which inhibit large scale adoption of RFID systems. RFID based inventory management systems are identified as a killer application which will drive excess capacity utilization in communication bandwidth and drive growth in the communication and computer industry. It also details the focus of this thesis research at analyzing cost drivers for RFID tag manufacturing and exploration of disruptive technologies for low cost manufacturing of tags.

2 LITERATURE REVIEW

RFID have been used in applications as diverse as livestock tagging to automatic toll booths for over a decade. Still, the adoption of RFID as a replacement for bar codes has not taken place due to the costs for manufacturing being significantly higher. Since the potential applications for RFID tags for more intelligent application compared to barcodes exists, a survey of business press and academic journals was conducted. The aim of this undertaking was to get a perspective of wide range of applications RFID could be used for, benefits over bar codes and system architecture of the tags and the cost drivers for manufacturing.

2.1 Applications of RFID Systems

RFID technology has been used since the 1940s to identify friend or foe for military airplanes. A more widespread application of this technology has been in the cattle industry for livestock tagging.[1] Since 1900 around 80 to 100 million livestock, have been tagged using RFID tags from Texas Instruments. This application is all the more relevant in recent times with the incidence of Mad Cow disease and Bird Flu and the corresponding need to be able to track the meat supply through the entire food chain.

As described in the research report[2], RFID systems can enable better tracking of assets, real time monitoring of supply chain inventories and more efficient payment processing. It is reported that in the consumer products industry over $9 billion is lost due to incorrect shipments of goods. Use of barcodes does not solve the problem since the process of reading the barcodes is still a manual process. Since RFID enables automated, real time gathering of inventory data, the potential for errors is eliminated to a large extent. General Motors currently uses RFID tags to track the movement of auto chassis at various stages in the assembly plants.[3] GM plans to use these tags to track individual components when the cost of the tags is reduced. A key benefit of using RFID based systems in the assembly plants is that it can automatically signal when an assembly tray has a mismatch of components or missing components required for completing the assembly operation. This helps significantly in early detection and prevention of bottlenecks in the manufacturing line.

A more widespread application of this technology is the Exxon Mobil SpeedPass system which is currently used by more than 5.5 million consumers for gas at the pump for goods purchased at the convenience stores in the gas stations.[4] Similarly retail stores like Stop & Shop Supermarket are evaluating key "fob" attachment which can be used in a manner similar to Smartcards to pay for groceries. If the RFID tags become as inexpensive as the barcodes and are used to tag each individual item, it is quite possible to eliminate the checkout counters at stores and use automated payment processing systems which are built using RFID technology. Another interesting application of the RFID technology is tagging of medical instruments and sponges to prevent them from being left behind during a surgical procedure causing injury or death. Surgical Resources has patented a RFID tagged sponge for this application.

The brief overview of current applications of RFID tags is presented with the objective to convey the wide diversity of applications and industries they are currently employed in. The breadth of application of this technology is only limited by the human creativity in incorporating this to deliver value from end user perspective while providing a compelling business case.

2.2 Benefits of RFID tags

Over 5 billion barcodes are scanned each day. For RFID tags to replace barcodes, they must present a compelling value proposition at reasonable cost. Some of the advantages of RFID tags over barcodes are linked to the ability to store information in the tags which is dynamic i.e. it can be updated if required. They do no require line of sight for readouts and the tags can be read in a multiplexed fashion. Real time monitoring of stored information is possible with the RFID tags which can be transmitted to a database through a wireless network. Since the memory capacity of RFID tags is much more than barcodes, amount of information which can be stored in the RFID a tag is significantly greater than barcodes. RFID tags have ability to integrate additional functionality like environmental monitoring of temperature, humidity or pressure through embedded circuitry. This functionality is not available using barcodes and the information stored is static. A summary of key differentiators between barcodes and RFID tags is listed in Table 1.

Barcodes	RFID Tags
Line of sight required for readout	Non-line of sight readout possible
Serial readout	Multi-plexed readout, with real time access
Information stored is static	Information content can be modified
Capacity of information stored is limited by barcode	Memory capacity can be augmented to store additional information
Environmental sensing not possible	Environmental sensing in real time possible with smart RFID tags
Insignificant cost of imprinting barcodes	RFID tags cost more than $0.05 in high volumes

Table 1 Comparison of key metrics for barcodes and RFID tags

2.3 Cost Reduction for RFID Tags

Significant research has been done at the Auto-ID center at MIT to investigate the cost drivers of RFID tags. Most of the work has been aimed at analyzing the traditional architecture of the RFID tags in terms of subsystems and then exploring incremental innovations to reduce the cost of manufacturing for primary cost drivers in the manufacturing process. One of the key drivers of costs using standard semiconductor techniques is the capital outlay for expensive lithographic equipment. Assuming a cost target of 1-2 cent per die, and a wafer processing cost of $1000, a die size budget of 500 microns/side has been proposed.[5] The Auto-ID has also proposed elimination of testing at wafer and die level which is carried out in traditional IC manufacturing processes in favor of testing after the tags have been packaged. This enables high throughput since the tag functionality can be read in a multiplexed manner and eliminates the need for expensive pick and place equipment to handle the minute dies. This is possible since the die cost and packaging cost of the RFID tags is negligible assuming a high yield as a result it is more economical to enable high throughput testing at the cost of discarding a small percentage of packaged defective dies.

Since the RFID silicon dies are minute, non-traditional approaches have been explored to enable high throughput assembly of the die to the antenna and the substrate. Verma et al. have pioneered fluidic self assembly techniques to eliminate the need for robotic assembly equipment.[6] Scharfeld provides a detailed description of the principle of operation of RFID systems and the fundamental constraints on low cost passive RFID tags.[7]

2.4 Emerging Manufacturing Techniques

Chou et al have pioneered the use of nanoimprint lithography for printing feature sizes below 25 nm over a large area with high throughput and low cost[8] Extension of this work in applying nanoimprint lithography using multilayer resist methods has been done by Xiaoun et. al.[9] Scheer et. al. have identified temperature to be a critical parameter for optimal transfer of patterns using nanoimprint lithography.[10] They have demonstrated nanoimprint technique to be a very optimal method for transferring periodic patterns with minimal variation in pattern size.

Cheong et al. have demonstrated the application of inkjet technology for the printing of copper source/drain metallization for amorphous Silicon Thin Film Transistor.[11] The elimination of processing steps and use of standard low cost inkjet printing technology can be applied to high throughput, low cost RFID tag manufacturing in the future.

2.5 Chapter Summary

The literature survey conducted to understand the historical use of RFID tags is summarized in this chapter. In addition, emerging applications of RFID tags as a replacement for barcode based systems are reviewed. Summary of the cost drivers for RFID tags as identified by the Auto-ID center is also presented. A survey of current trends in areas of emerging manufacturing techniques for low cost, high volume manufacturing of semiconductor chips is also reviewed in this chapter. This survey was the foundation for a more detailed research and analysis of disruptive technologies which might be employed for reduction of RFID tag manufacturing in the future.

3 RFID-RADIO FREQUENCY IDENTIFICATION TAGS

RFID technology has been in use for over a decade. Texas Instruments has been an innovator in this field and according to their estimates, approximately 80-100 million livestock have been tagged using RFID technology. With the recent attention due to the occurrence of Mad Cow disease, livestock tagging and the tracking of meat and poultry products throughout the supply chain has gained significant importance. In addition the recent announcements by Wal-Mart requiring its top 100 suppliers to start tagging their shipments using RFID technology on all pallets, cartons and cases and high margin items by 2005 has given a huge impetus for the wider adoption of RFID technology. [12] A similar directive has been issued by US Department of Defense.

3.1 RFID Technology Overview

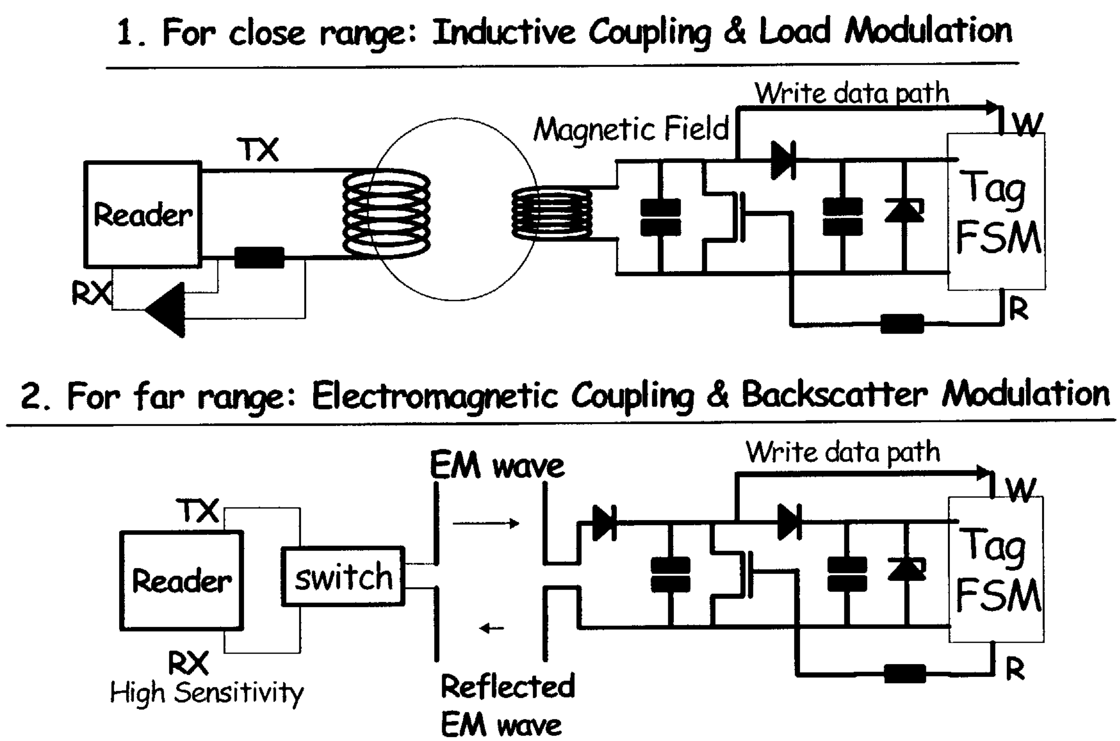

Figure 2 RFID Operating Principle[13]

As shown in Figure 2, RFID works using wireless transmission using tags. Line of sight, orientation constraints are eliminated compared to traditional tagging mechanisms such as bar codes. In addition, multiple readouts can be achieved and transmitted in real time to processing location. The RFID system works through electromagnetic induction initiated by the presence of a RFID reader in close proximity (<10 meters) of the tagged element. The induced current in the RFID tag is used to charge a capacitor. The stored charge in the capacitor activates the diode element which activates the RFID tag circuit which transmits the stored tag number in binary form. The binary code pulses the parallel transistor which in turn causes load modulation of the reader coil induced current. These changes are sensed by the reader circuit element and converted to digital format. [14]

In case of RFID system with higher scan ranges, a digital signal is used to generate a RF signal which is transmitted using a dipole antenna. The potential difference induced across the tag terminal causes electric current to charge the capacitor and the system functions in a similar manner as low frequency system.

3.2 Applications of RFID

RFID technology is currently used by the early adopters. Usage scenarios include RFID enabled identification badges used in companies, Toll checkpoints, Supply chain management of high value items and drug tracking to prevent counterfeiting. Another critical usage scenario would be use of RFID tags to identify and track medical samples in the healthcare industry. This would eliminate significant source of medical errors. In the semiconductor manufacturing industry, RFID tags can be used to track wafer boats through the fabrication facility. This will enable more efficient processing and testing of manufacturing lots as the wafers proceed through the fab. A critical point to note is that current generation of 130 nm microprocessors needs to go through more than 450 activities during the manufacturing flow itself. In addition the assembly and test operations have additional steps and are usually done in different globally dispersed locations.

Company	Usage	Status
US cattle industry	Livestock tagging	1982
Toll Operators	Ezpass toll payment	Deployed
ExxonMobil	Speedpass gas payment	Deployed
7 Eleven	VIP-Automatic bill payment at cash register	Deployed
GM	Parts inventory management	Deployed
Walmart	Pallets, cases and high margin items for top 100 suppliers	2005
Walmart	Pallets, cases and high margin items for all 100 suppliers	2006
DOD	Pallets	2005
Electronic Arts	Pallet level video game shipments	Pilot
Metro AG	Future Store	Pilot
Target	High value consumer electronic items	Pilot
Best Buy	High value consumer electronic items	Pilot

Table 2 Sample of RFID solutions under investigation

The inherent advantages offered by RFID tags of zero human intervention in enabling inventory tracking of high value items (relative to cost of RFID tags) makes a compelling case for using it to reduce operating expenses. Contrary to widely published claims by industry analysts of potential savings through more efficient supply chain management for retailers like Wal-Mart, the greater expense reductions will come through significant reduction in expenses incurred for inventory tracking. UK based retailer, Mark & Spencer has reported reduction in EPC readings from 29 seconds to 5 seconds for each dolly in their fresh foods operation.[15]

Despite the apparent advantages of RFID tags of remote tracking, multiple readouts and orientation independence for readouts, its operation is impacted by metal structures and containers filled with liquids. For a widespread adoption of this technology, the price of tags need to come down from the current level of 50 cents to less than 5 cents to enable item level tagging. This may be enabled in the future by the application of advanced lithography techniques such as nanoimprint lithography. In the meantime there are significant applications where this can be used right now. IDC expects the RFID spending in just the US retail chain to increase from $91.5 million in 2003 to $1.3 billion in 2008.[16]

3.3 Implications for Communications & Computer Industry

It has been estimated by Retail Forward, that if every item in Wal-Mart were tagged with RFID then 7.7 terabytes of data would be generated each day. Clearly this will not be a practical reality for a long time in the future and its usefulness is also questionable. It is quite clear with the gradual rollout of RFID technology; the amount of data generated for better supply chain management will require significant communication bandwidth in addition to greater demands on a distributed computing infrastructure. Significant increase in deployment of wireless LANs throughout the supply chain in addition to a sharp increase in the bandwidth usage in transmitting inventory data in real time will require additional capacity upgrades to the infrastructure in these two industries. In order for the technology adoption to cross the chasm from early adopters to early majority and latter stages in the technology life cycle for RFID, standardization of the EPC code is required. Major developments in the middleware development will need to be undertaken in order for the companies to process the huge volumes of real time data generated by the RFID tags. Without this enabling technology, companies will not be able to reap any benefits of RFID technology.

3.4 RFID Types

3.4.1 Passive RFID Tags

Passive RFID tags are the simplest RFID tags. They do not contain any power source. The data embedded in these tags is transmitted through modulation of the magnetic field of the readers. They are manufactured in a variety of form factors which include wafer thin label form factor. The data storage capacity ranges from few bytes to few kilobits. The read distances are limited to less than few meters. Typical applications include animal tracking, retail merchandising and smart paper labels.

3.4.2 Active RFID Tags

Active tags have an embedded power source. Due to the presence of power source, they enable faster data rates for reads and also greater read distances. Data storage capacity can approach 2 MB and are suited for applications which require encryption and noise immune operation in the presence of electromagnetic fields. They are typically used in factory automation systems, asset tracking and rail industry. Due to the faster data transmission rate and higher storage capacity, they can be used in applications which require multiplexed readouts in a short time interval. Readouts can be obtained at distances of up to 30 meters.

3.4.3 Inlays

Inlays are ultra thin tags which may have a paper or polymer substrate and usually produced using roll to roll manufacturing. They are passive elements which are usually used in applications where cost is of primary concern and read distances are usually less than 6 meters. Data storage capacity is less than 256 bits. Typical applications include airline baggage ticketing, document control, access control and general logistics management of low value items in large quantities. A comparison of functional specifications for typical RFID tags is illustrated in Table 3. A classification tree for different components of RFID tags is illustrated in Figure 3.

RFID type	Min Freq	Max Freq	distance	dimensions	weight	memory	data durability	temperature	Cost
passive	125Khz	2.45 Ghz	6 m	0.8mm	6-54g	16Kbit	10 yrs	-40-70 C	$1.00
active	132 Khz	2.45 Ghz	30 m	40mm	120-320g	2Mb	10 yrs	-10-50 C	$20
inlays	13.56 Mhz	915 Mhz	6 m	30mm	80-200mg	256bits	10 yrs	-25-80 C	$0.40
* SMARTCODE RFID tags									

Table 3 Typical Functional Specifications for RFID tags

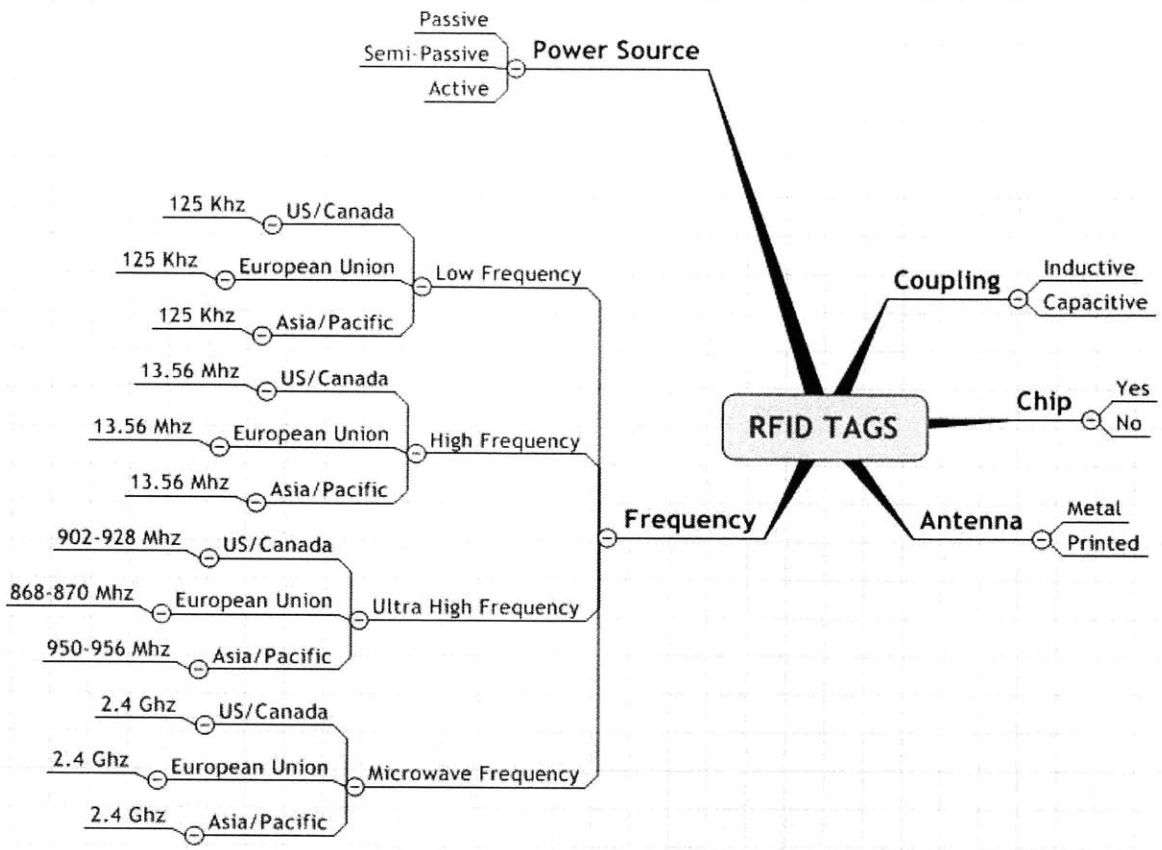

Figure 3 RFID Tag Classification

3.5 RFID Operating Frequencies

RFID tags operating frequencies typically fall into four frequency ranges. Low Frequency (LF) range corresponds to frequencies less than 125 KHz. The data rate is slow and the read ranges are limited to less than 1 meter. They are best suited for access control, animal tracking and Point of Sale applications.[17]

High Frequency (HF) range corresponds to frequency of 13.56 MHz and has a read range of about 1 meter. They are used for access control cards and retail inventory tracking.

Ultra High Frequency (UHF) range corresponds to frequencies in the range of 860 MHz to 930 MHz. Read ranges is limited to 3 meters. They operate at higher power levels and are used for supply chain applications for pallet and case level tracking. The readout rates are also much higher compared to lower frequency ranges.

Microwave Frequency (μF) range corresponds to 2.45 GHz to 5.8 GHz. The data rates are the highest at this frequency and are used for airline baggage tracking.

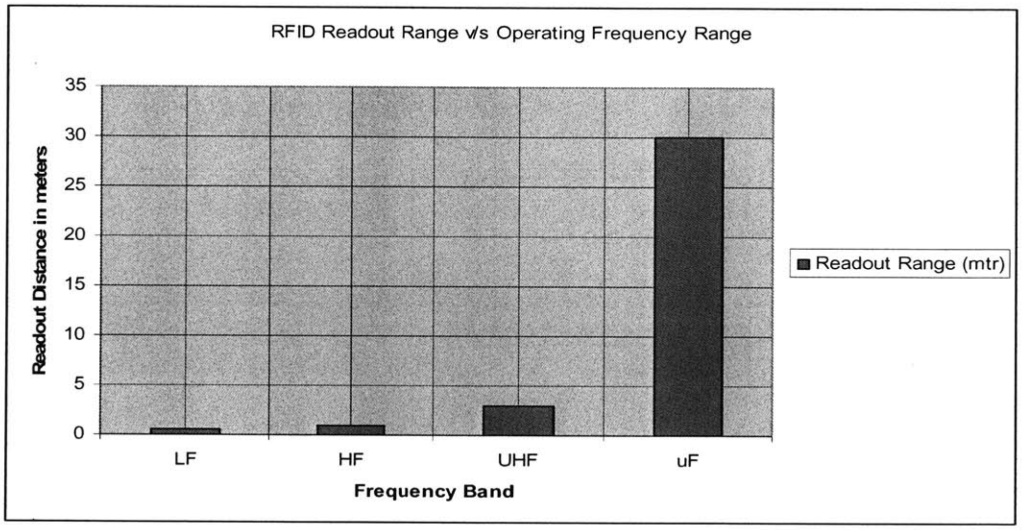

Figure 4 RFID readout range as a function of operating frequency

3.6 Chapter Summary

In this chapter we review the principle of operation of RFID based systems. A brief overview of technology using inductive coupling and electromagnetic coupling is presented. A detailed review of current applications of RFID based systems is also reviewed along with timeline for adoption. A particular critical application in the healthcare industry for automated tracking of medical sample and records is discussed as a source to reduce incidence of medical errors. The implications of widespread adoption of RFID based systems and the huge amount of real time data generation is reviewed in terms of its impact on the bandwidth utilization and the impact on the communication and computer industry. The classification of RFID tags is presented along with the frequency spectrum of RFID use in the world is summarized.

4 COST DRIVERS FOR RFID TAGS

We explore the components of RFID tags in this section and discuss the cost drivers of the individual subsystems for the RFID tags. Then we explore the current approaches for manufacturing RFID tags and discuss the applicability of future manufacturing processes to reduce the cost of RFID tags.

4.1 RFID Tag Architectural Decomposition

RFID tags typically consist of an integrated circuit die which is comprised of the RF (analog) front end and the digital circuitry which includes the memory storage component wherein the tag information is stored. The antenna is in the form of a conductive element which is shaped for optimal impedance matching with the reader coil. It is connected to the IC die through a conductor. The assembly of the antenna and the IC die is attached to a flexible substrate which is then housed in a package.

A modified architectural decomposition of a RFID tag developed by the Auto-ID center is shown in Figure 5. The three main subsystems in a RFID tag are the Analog Front End, Detection/Encoding & Anti Collision Detection and the Memory. The architecture illustrated has an additional component which is responsible for environmental sensing. This can be used for temperature, humidity, pressure, odor or any other sensing scheme. This can be an optional functionality incorporated to meet application specific requirement. We will discuss the feasibility of incorporating this functionality using some of the emerging manufacturing techniques in later sections when we review paper on chip assembly techniques.

The Auto-ID center has proposed minimizing the amount of memory and functionality within a RFID tag to minimize the die size with the objective of minimizing die cost through increased yield. An important point to bear in mind is the yield curve has an exponential dependence on the defect density and the area of the die. This is evident from Equation 1.[18]

Yield = exp (-D*A) Equation 1

D = Defect density = Number of good dies/ wafer

A = Chip die size

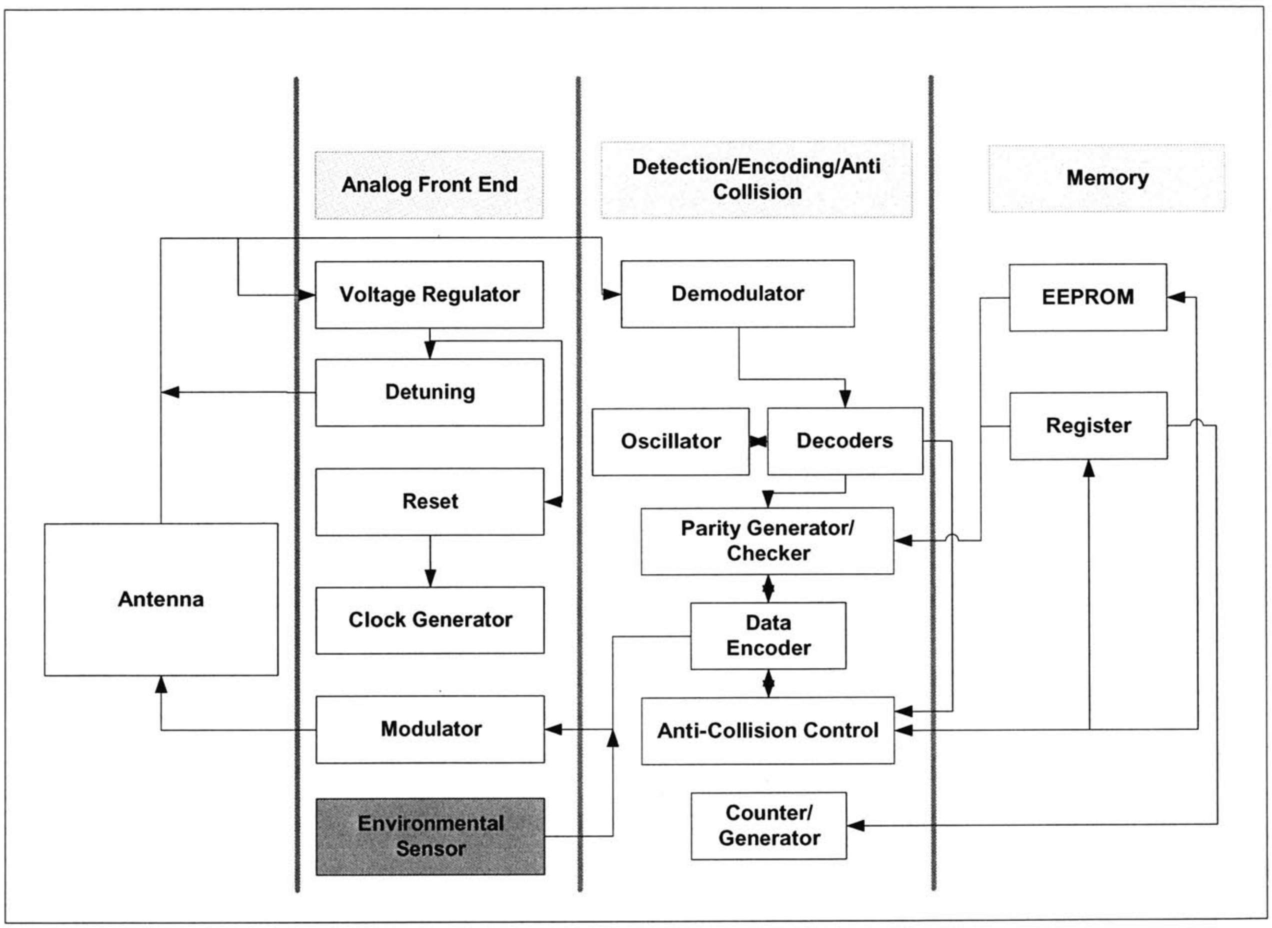

Figure 5 RFID TAG Architectural Decomposition

In standard semiconductor manufacturing processes the IC dies are tested for correct functionality before they are packaged. The wafer level testing and screening is referred to as sort testing. This is due to the significant cost incurred for packaging process and also the wasted tester resources if this test were to be skipped and the resultant defective die was weeded out during test after packaging operation. A typical process flow for high volume test and validation of an integrated circuit die is illustrated in Figure 6.

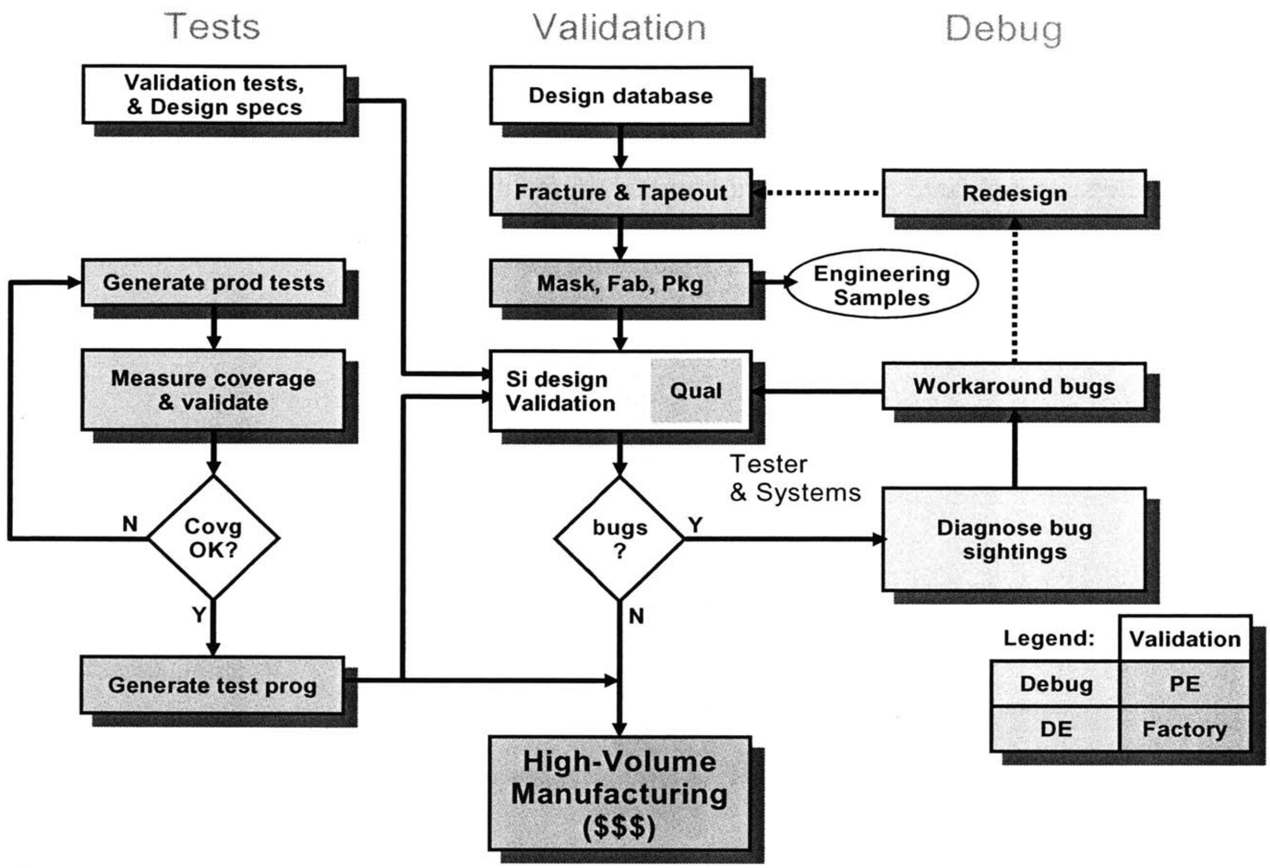

Figure 6 Semiconductor IC Test Process Flow

Current tag costs are around $0.45. The major components of the cost are illustrated in Figure 7. As observed from the distribution, the manufacturing process of the IC die constitutes the major cost component. This is attributed to the cost of expensive photolithographic equipment associated with conventional semiconductor manufacturing processes. Even though the latest generation processing capability is not required, still the costs of clean room lithography processes are significant. In addition, since the die area of the RFID tags is very small, significant wafer area is lost due to scribe lines trenches which are used to separate individual dies.

The assembly costs for connecting the IC die to the antenna and packaging it in a substrate are also significant. This is due to the necessity of precision pick and place robotic assembly lines for high throughput operation. This problem is even more severe for the RFID tag due to the miniature die size compared to traditional logic IC. In reality, traditional flip chip packaging and pick and place assembly techniques are not suited for RFID tag manufacturing.

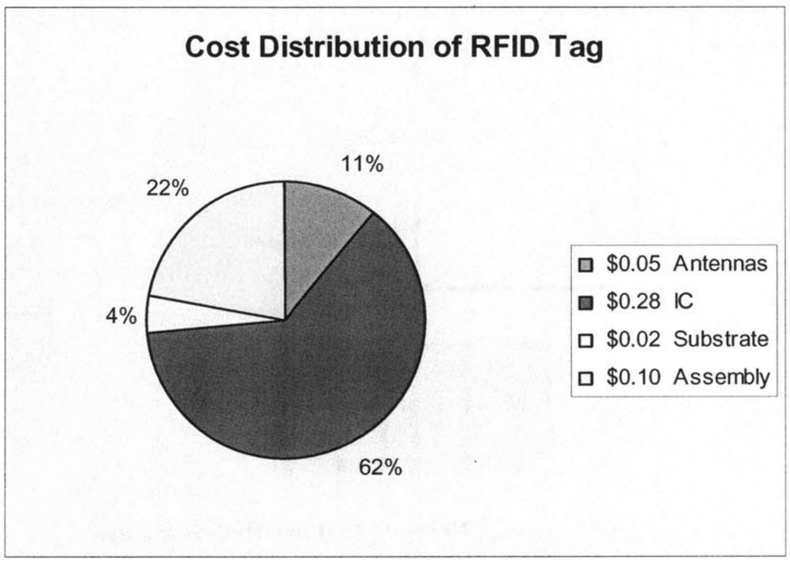

Figure 7 Cost distribution for RFID Tag

4.2 Cost Benefit Analysis

As shown in the value definition framework developed by Prof. Crawley at MIT, value is defined as benefit at cost. For RFID based inventory management systems, the benefit of real time monitoring of inventories and the overhead in implementing a backend infrastructure to process the real time data collection needs to translate in end user benefit. The cost of RFID tags and the entire system has to result in an ROI in terms of reduced shrinkage, stock outs, lower inventory holding costs or any other benefit described earlier which is significantly superior to a supply chain management system which is based on a barcode. It has been estimated that almost 2.3% of Walmart's sales is lost due to stock loss. This amounts to almost $6 billion in lost revenue. Brian Subirana from the Auto-ID center has stated that almost 1.1% of Walmart sales are lost due to unsellable items. This amounts to $3 billion.[19] The use of real time inventory tracking can be used in a manner to deliver end user benefit to a retail chain like Walmart to reduce the loss by an amount greater than the cost of implementing the RFID system. The Auto-ID system has developed a process to map the process flow used to track the inventory and the time spent on it along with a method to estimate the potential for improved efficiencies in supply chain management using RFID based system. It is critical to use this systematic process to evaluate the ROI of replacing or enhancing the barcode based systems with a more expensive RFID tag based system. Some of the simpler enhancements to improve stock loss visibility is the use of Pareto analysis to identify the products contributing to the maximum amount of theft and the list of stores which contribute to the maximum amount of theft. A recent study by the Auto-ID involving BWS Sainsbury's showed 20% of SKUs accounted for 50% of loss and 18% of stores accounted for 50% of losses. This information can be used for more targeted monitoring of the "Hot" product and stores with cheaper alternatives than a wide scale deployment of RFID based tagging schemes for every item in the inventory.

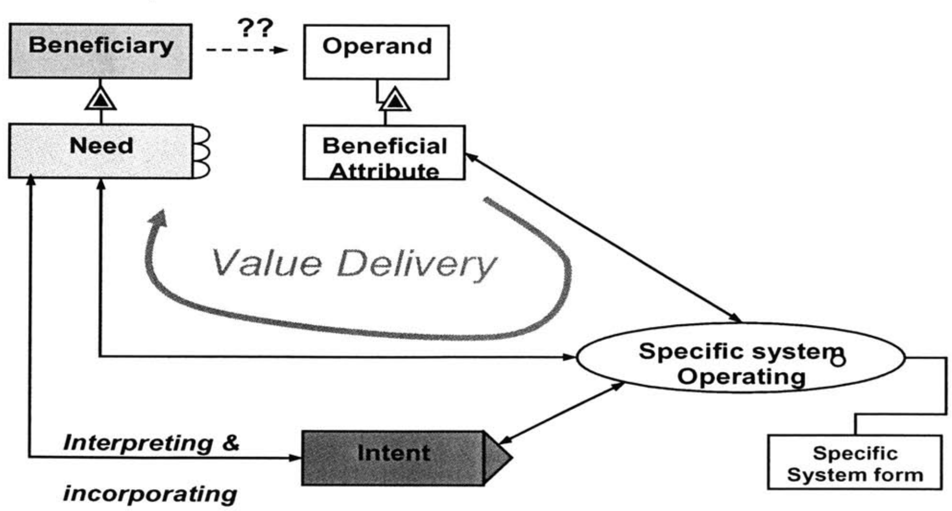

Figure 8 Value definition framework[20]

4.3 Chapter Summary

In this chapter the cost drivers for RFID tag manufacturing are discussed along with a discussion of the difficulties in scaling traditional semiconductor manufacturing processes for RFID IC manufacturing. The expensive lithographic equipment and non scalability of robotic pick and place assembly equipment are identified as two key factors limiting cost reduction for RFID manufacturing. A system architecture decomposition of the RFID tag is also discussed along with a modification to enable implementation of smart RFID based sensors which will increase complexity of RFID tags and hence costs using traditional manufacturing processes. In this section the primary focus of cost are the tags. It is recommended to perform a detailed cost benefit analysis of implementing a RFID system while taking into account all components of the RFID system which would include reader costs, middleware and business process redesign related costs while evaluating simpler alternatives like enhancing existing barcode based supply chain management solutions.

5 INDUSTRY ANALYSIS

5.1 Value Chain Analysis

This chapter reviews the industry structure and the value chain in the RFID industry. This will serve as a foundation to understand the locus of innovation and the impact of disruptive technologies which may be employed for manufacturing of low cost RFID tags and systems in the future. A detailed review of potential low cost manufacturing solutions is discussed in the next chapter. Figure 9 shows the current RFID value chain.

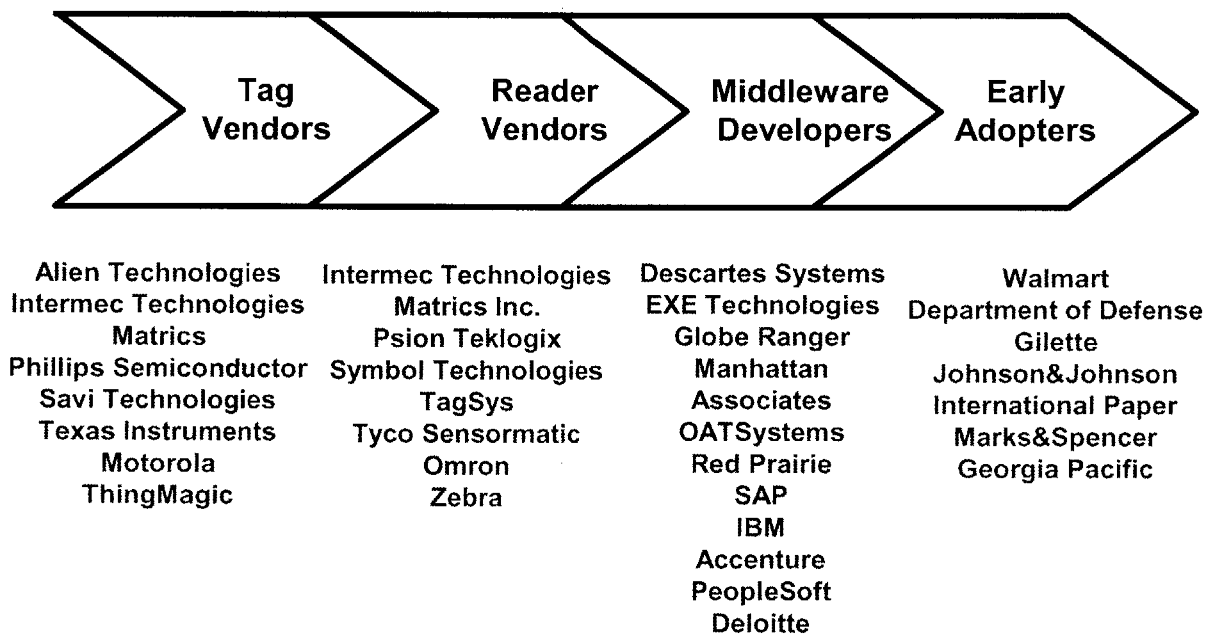

Figure 9 RFID Value Chain[17]

5.1.1 Tag Manufacturers

As seen from the above value chain, except for Texas Instruments and Motorola, none of the major IC design manufacturers are represented in the value chain. Although this may be attributed to the relatively low margin on the ASP[1] of the RFID tags, it is also due to the radical innovations in product architecture and manufacturing techniques required to reduce the cost of RFID tags to below $0.05 to make it a candidate for high volume adoption to replace barcodes. As seen from Figure 10, the revenue contribution from the RFID tag segment is almost equal to the contributions from the sum of all remaining segments. The total revenue for 2002 was estimated to be $964 million and for 2003 it was $1.1 billion.

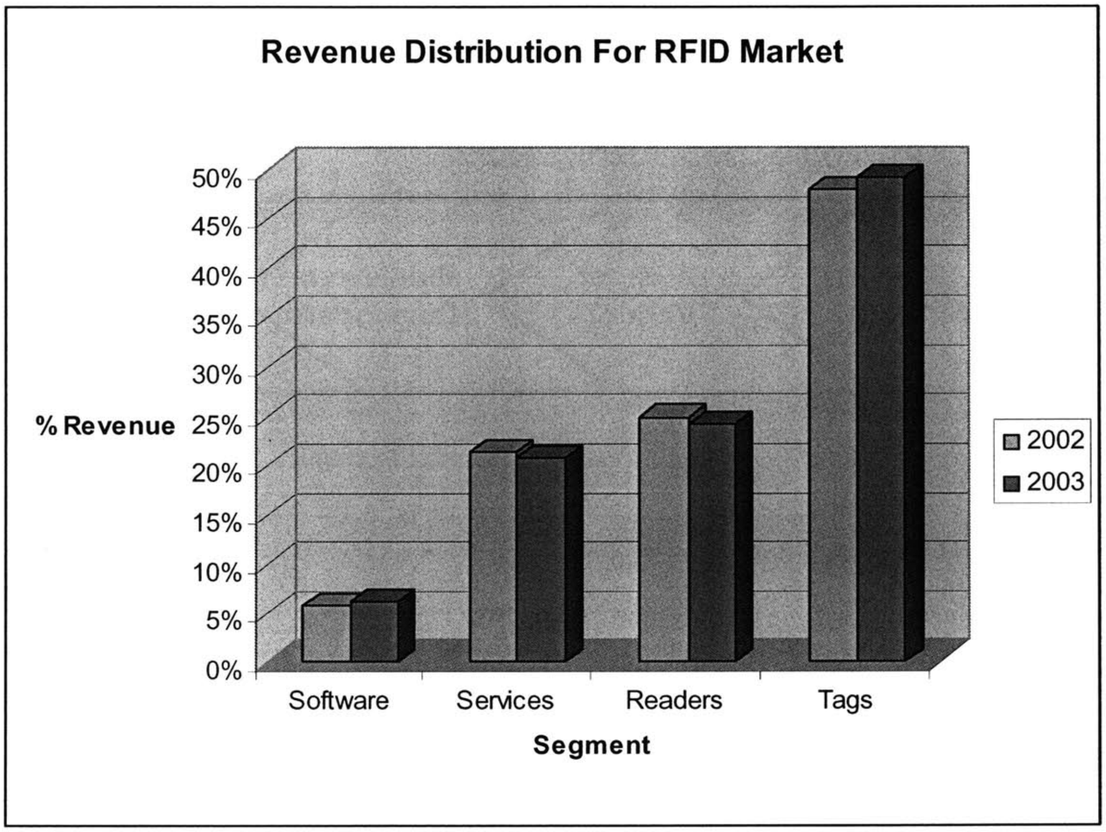

Figure 10 Revenue distribution for RFID market (Source: Bear Stearns, VDC)

Matrics technology offers a range of EPC compliant Class 0 and Class 1 tags. They are targeted for the UHF frequency range which is suitable for pallet and case level tagging. Matrics has also developed a proprietary method of assembly called the PICA (Parallel Integrated Circuit

[1] ASP Average Selling Price

Assembly) which enables rapid assembly of the die, substrate and the antenna at low cost. This method is described in more detail in Chapter 7.

Alien Technology manufactures Class 1 EPC compliant RFID tags using the Fluidic Self Assembly process. This is described in more detail in Chapter 7. Alien's product range covers both the ultra high frequency and the microwave frequency range for applications in pallet, case, logistics and airline baggage tagging. Alien recently received an order from Gillette for 500 million tags for tagging consumer products in the retail chain.

Texas Instruments is one of the leading semiconductor manufacturing companies which has been engaged in providing high frequency (13.56 MHz) RFID tags for over three decades mainly for livestock tagging applications. Their current portfolio is targeted at item level tagging applications using Class 0 tags which have limited range. It is quite possible that TI would either license technology to offer a broad range of EPC compliant tags or acquire one of smaller companies with a complementary asset portfolio.

5.1.2 Reader Vendors

The market share of readers is more than 25% of the total RFID market. Since profit margins from the sale of the readers are much higher than that derived from the sale of tags, it offers a compelling business case for market entry. Most of the RFID tag manufacturing companies are engaged in this space. Till there is clear adoption of industry standards and the customer require the functionality of tags and readers to be independent of suppliers, it is quite possible for a proprietary solution to be offered for readers. Since the design of the readers can be based on modular architecture, COTS[2] technology can be used for its development. With the adoption of industry standards, horizontal disintegration may result in vendors to be engaged in design and manufacturing of readers independent of tag manufacturing.

[2] COTS Commercial off the shelf technology

Intermec Technologies is the leading company in the barcode printing and scanning domain with a lock in over related IP. They also have a product portfolio to cover the entire frequency spectrum of RFID tags and readers. Both Intermec and Symbol Technologies offer RFID readers with integrated barcode scanners due to their historical presence in the barcode domain.

Matrics manufactures multi-point readers as well as single point readers for embedded applications like PDA or printer based applications to enable context aware applications. Tyco Sensormatic which was formed with the acquisition of Sensormatic by Tyco is also a major player in the handheld and stationery reader design space. Sensormatic has been involved in design of electronic article surveillance solutions for over three decades.

5.1.3 Middleware

As expected most of the software companies involved in the ERP domain are also engaged in developing middleware and applications for enabling RFID based inventory management systems. The availability of software applications is key to process the huge amounts of data generated by wide scale adoption of RFID based systems. Efficiency improvements in the supply chain may be constrained by the lack of middleware. Some amount of collaboration is evident in partnerships with tag manufacturers, reader vendors and middleware developers. One example is the partnership between Manhattan Associates, Alien Technologies and Symbol Technologies along with Accenture to provide an integrated solution for RFID based supply chain management.

5.1.4 Early Adopters

As discussed earlier Walmart and Department of defense are the earliest adopters of RFID based supply chain management solutions. They have targeted pallet and case level tagging using RFID tags. At this level of granularity the cost of RFID tags is not a issue for concern at its current cost. Gillette also has placed the largest order for RFID tags from Alien Technology for half a billion tags. In addition some of the largest companies in the consumer and retail products chain are switching over to RFID based systems at least at the case or pallet level. This enables more efficient inventory management at the same time offers significant reduction in operating expenses and faster throughput in inventory tracking. Mark & Spencer, a British retail chain has started using RFID based inventory management for its refrigerated food supply chain and has reported over 80% reduction in time to track its inventory.[17]

5.2 Industry Structure

Texas Instruments has been a pioneer in the field of RFID since the last couple of decades. It has accounted for sales of over 200 million RFID tags over the last decade. It has mainly targeted frequency ranges below 13.56 MHz aimed at applications like livestock tagging, access control, automotive and wireless commerce applications like the ExxonMobil Speedpass shown in Figure 11.[21] TI has been a vertically integrated solutions provider till recently and has offered an entire suite of products covering the RFID tags, readers and software for implementing an end to end solution for access control and inventory management. However, it has been a slow adopter of the EPC standard developed by the Auto-ID center.

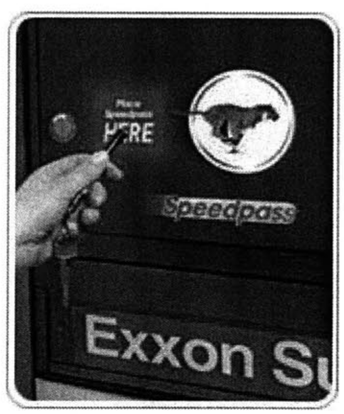

Figure 11 ExxonMobil SpeedPass[22]

Recently the industry has witnessed the introduction of RFID tags compatible with EPC standards from a number of competitors. A similar phenomenon is seen in the number of companies developing RFID readers and engaging in middleware development. This stage could mark the creation of a dominant design as described by William Abernathy and James Utterback.[23] As described by Professor James Utterback, emergence of a dominant design marks the culmination of a flurry of radical innovation with the emergence of a standard design. This leads to an expectation from the marketplace of existence of a standard set of features and functionalities from the product. The focus then shifts to incremental innovations and the rate of process innovations increases. This can be seen in the standardization of the features of the RFID integrated chip to some extent and the shift to development of process equipment which are aimed at high volume manufacturing and packaging of the RFID tags. It is quite possible that the definition of dominant design for RFID tags might change over time with the integration of smart sensors with the RFID tags for environmental sensing for specialized application. The model of dynamics of innovation developed by Utterback and Abernathy is shown in Figure 12.

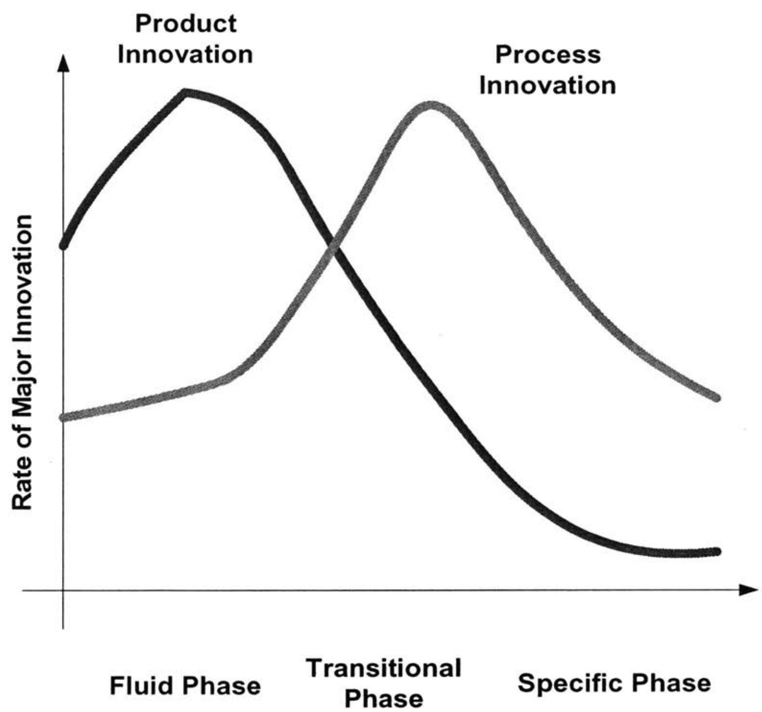

Figure 12 Innovation during product life cycle

The design of RFID tags compliant with the EPC standards is still in the early stages and is marked with the difficulty experienced in the interoperability of tags and readers manufactured by different vendors. As a result, companies in the RFID industry are focusing on vertical integration to provide readers and tags which are compatible. Once interoperability standards are established we can expect to see disintegration of the industry with specialized companies manufacturing RFID tags, readers, manufacturing equipment for the tags and middleware software. This will follow a pattern which has been observed historically observed in multiple industries like the personal computer, automobile and bicycle industries to name a few. This is basis on which Professor Charlie Fine developed the double helix model of business dynamics which is shown in Figure 13.

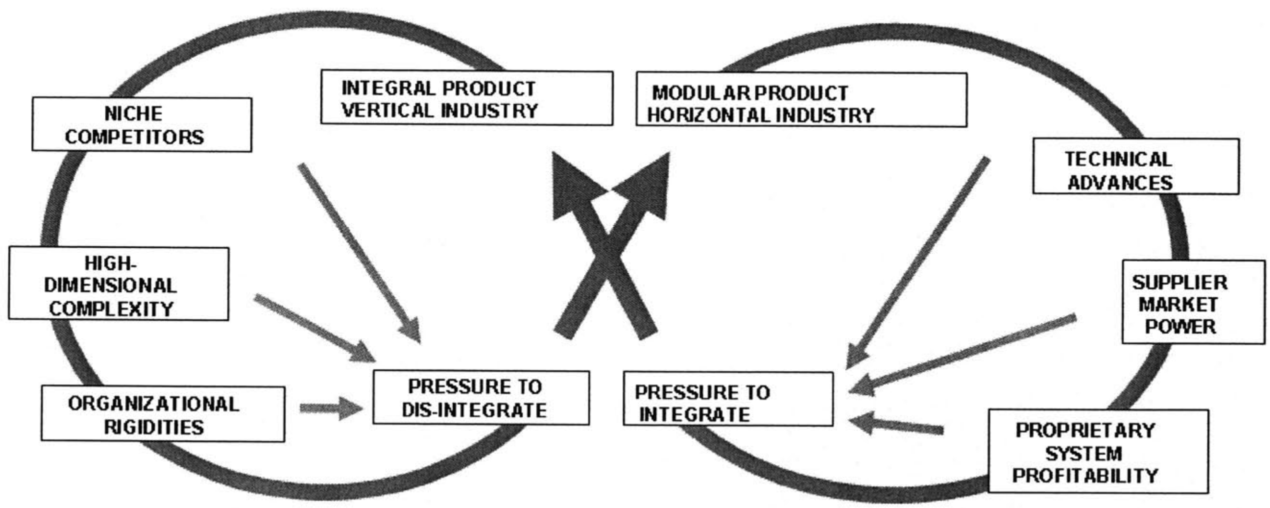

Figure 13 Double Helix Model[24]

If a member of the value chain transitions into a position to command considerable leverage over the entire value chain, it may try to extract additional value from the value chain by pursuing a strategy of vertical integration. This can happen if a manufacturer of readers develops a design which has high throughput RFID tag readout with maximum accuracy under noisy environment, security and range and commands a significant market share, then it may acquire or partner with RFID tag manufacturing company to control a larger portion of the value chain.

Examples of this strategy are quite evident in the PC industry. With the scaling trends enabled by the realization of Moore's Law, Intel has maintained a technological trajectory of integrating additional features and functionality like graphics capabilities and wireless networking into the processors and chipsets respectively. This is similar to the strategy pursued by Microsoft in bundling additional components into the operating system. A similar scenario may be observed in the future with respect to the software subsystem of RFID systems wherein ERP vendors may incorporate middleware applications into their software suite to enable future supply chain management solutions.

Another possible scenario for vertical integration could be innovative solutions which enable source tagging. Innovations which lead to low cost integration of RFID tags with packaging material for pallets, cases or individual items may enable packaging suppliers to acquire or develop capabilities for RFID tag manufacturing to provide an integrated solution.

As shown in the double helix model, entry of niche competitors which offer specialized tags with integrated sensors for environmental sensing may lead to segmentation of the market. This may lead to companies developing specialized tags involving a high degree of technological complexity. Potential market segments for this include integrated sensors and active tags with wireless capabilities for remote sensing.

Another area where horizontal disintegration may occur is market segmentation of readers. Companies may develop readers which are targeted for either stationary or mobile inventory management. Alternatively companies may develop readers with a much lower power output for use in hospital environments in order not to cause interference with medical diagnostics electronic equipment.

5.3 Porter Analysis

A critical framework to formulate strategy to increase the profitability in any industry is the "Five Forces Model" developed by Michael Porter.[25] This model looks at the five forces:

1. Threat of entry
2. Threat of substitution
3. Bargaining power of buyers
4. Rivalry among competition
5. Bargaining power of supplier

Two additional factors can be added to this model. They are impact of regulation and uncertainty. This framework is valuable both from the perspective of an entrenched company in a value chain to maintain its competitive advantage and for potential entrants to develop strategies for entering a new market. Porter's five forces model is illustrated in Figure 14.

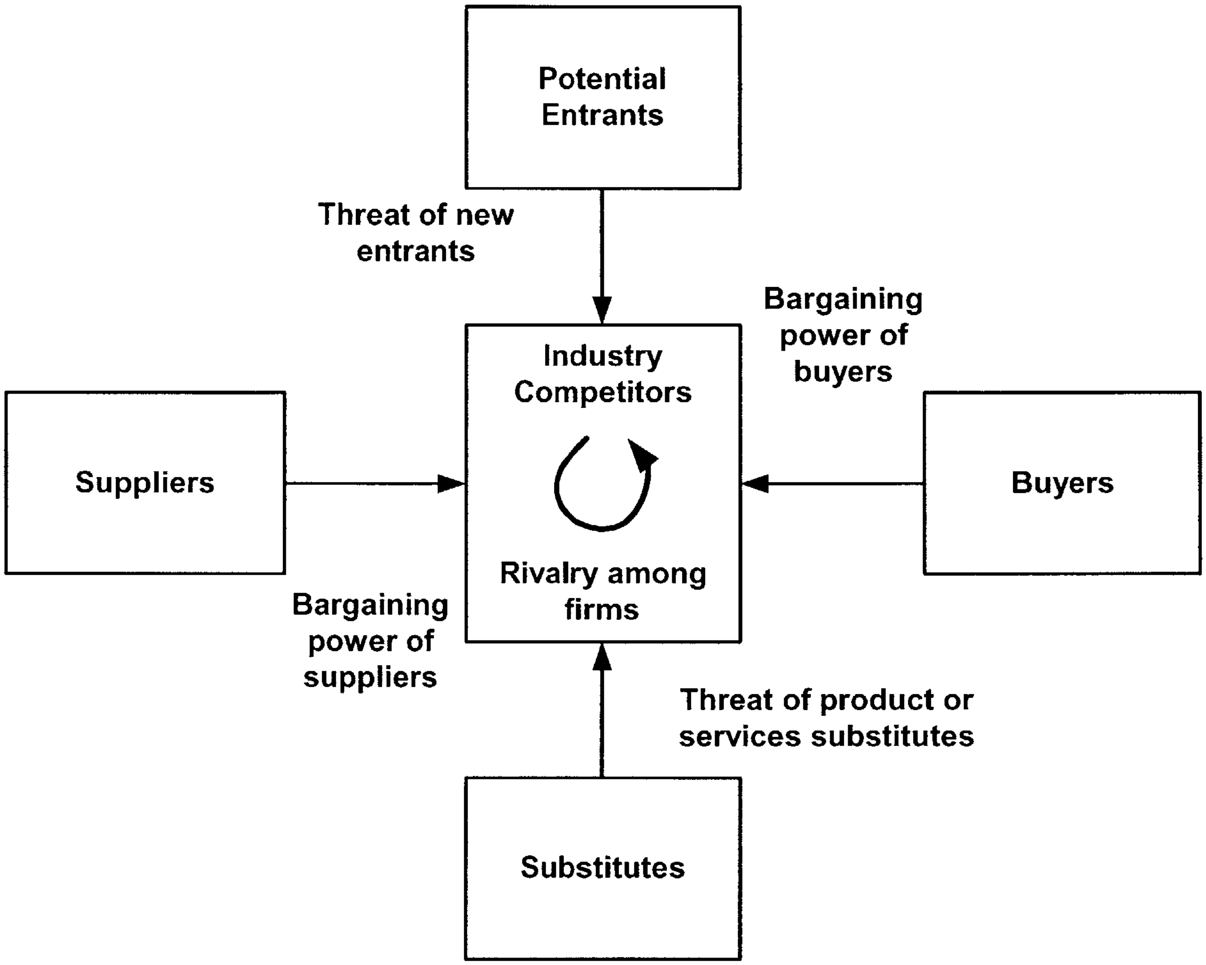

Figure 14 Forces Driving Industry Competition[25]

5.3.1 Suppliers

As discussed earlier in the value chain analysis, the key primary suppliers for RFID tags are Alien Technologies, Matrics and TI. This segment is marked by the absence of major semiconductor manufacturing companies such as Intel, IBM, Samsung, Toshiba, ST

Microelectronics, Hitachi and Motorola. This can be attributed to some extent to the fact that these companies focus on high margin segment of the semiconductor industry namely microprocessors. This leads to organizational rigidities and technology portfolio which are difficult to adapt to low cost, high volume RFID tags. For the reader segment, the silicon is supplied by established companies such as TI, Analog Devices and Motorola.

5.3.2 Potential Entrants

The barrier to entry for new competitors for the RFID tags is the extremely low profit margin and the necessity of radical innovation to meet the needs of sub $0.05 cost structure. The threat of entry by established companies in this segment is diminished by really low rate of expected return on invested capital due to the cost structure. It is possible for a leading semiconductor company to acquire or license technology and use its brand equity and economies of scale to offer a reliable solution and in the process command a brand premium. On the other hand, since the latest generation semiconductor processing is not required for manufacture of RFID tags, it is possible for new entrants to innovate in the realm of low cost, high volume semiconductor manufacturing and gain market share.

New entrants are likely to target the high end of the RFID tag segment which may have intelligent sensors embedded in active tags since this has potential for higher ASP. One area for such application specific tags would be for industrial monitoring. A possible entry strategy might be to target multiple use RFID tag applications (instead of single use tags) like transportation and automated payment. This could be accomplished through incentive schemes which recover the cost of RFID tags through revenue sharing schemes.

For the reader platform, it is a matter of time before general purpose silicon solution will become the standard for enabling all the communication and computation functionalities. This will limit the opportunities for companies providing custom silicon for reader platform development. Companies like Cisco and Sun could enter this segment to leverage their existing platform solutions for networking and communication. This is an attractive proposition since accelerated adoption of a RFID standard platform will drive industry growth which will result in increased utilization of network bandwidth and computation capability. This will drive revenue growth in the core business of both these companies. From this perspective, it would be an attractive proposition for Intel, IBM and AMD to enter this market segment. An option to be investigated is the impact of subsidizing cost of RFID tags to drive revenue growth through demand amplification of products in the core business. Porter proposes a critical framework based on ease of entry and exit which will determine profitability as shown in Figure 15.

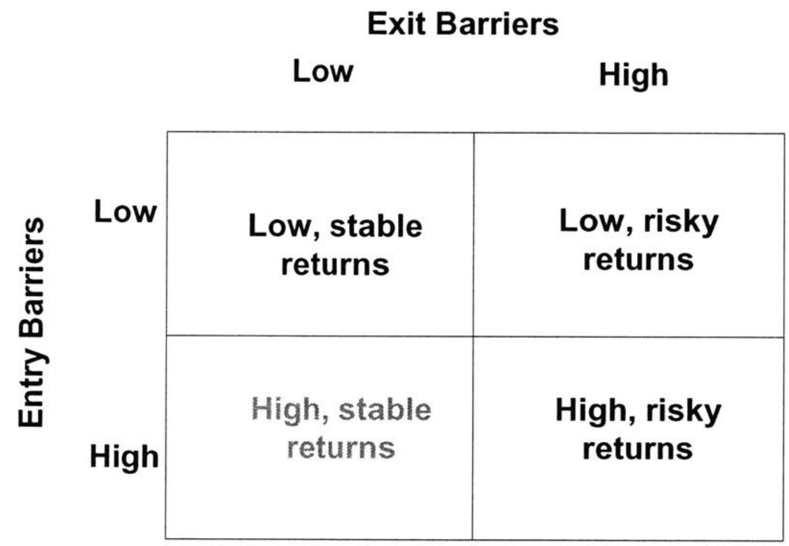

Figure 15 Porter Barriers and Profitability Framework[26]

Based on this framework, if a company can innovate and develop a solution for extremely low cost RFID tags, high throughput manufacturing and can defend its IP position then it could be rewarded with high stable returns due to the market size and growth potential. The exit barriers would have to be kept low by not depending on expensive lithographic manufacturing equipment. In addition the company will have to be agile in continuing to innovate to meet the future needs of the market to counter market segmentation and entry of niche competitors.

Similarly if a company can develop a reader system architecture based on modular platform with an open architecture to enable software development for multiple applications then it may be able to gain significant market share with stable returns. The assumption is that it will be able to leverage existing investments in subsystem development across multiple product lines and be able to provide a distinctive solution which meets the performance standards for complex applications which require reliable high throughput reads with superior capabilities for secure readouts and wireless functionalities. If a company enters a market with a custom solution then the capital investment will be high and application dependent and hence the exit barriers will be high.

5.3.3 Substitutes

For the RFID tags to see a wider adoption they need to offer a substantial benefit compared to barcode based schemes for inventory management at low cost. The RFID systems to should be able withstand competition from enhanced barcode based schemes which allow for increased information density through 2-D barcodes or similar mechanisms.

5.3.4 Buyers

The largest buyers for RFID systems are retail chains, government institutions like the Department of Defense and large corporations. A directive from large customers like Walmart, Procter&Gamble or Johnson&Johnson can accelerate the adoption of RFID technology at an accelerated pace. While it may be strategically important to identify and obtain design wins with these large customers, profit expectations from these large orders might have to be reduced since these customers have greater leverage from the companies currently in the RFID tag manufacturing domain. Orders from Walmart, Gillette and Department of Defense represent a significant portion of capacity utilization of Alien Technology or Matrics. Hence the ASP of the tags and the profit margin will be under significant pressure.

5.3.5 Rivalry among firms

Since RFID industry is still in its infancy, the number of firms entering all segments is on the rise. Since the RFID tag market size represents the largest revenue segment of the industry, we see significant number of firms entering this segment. Since the cost structure of this segment is quite low, we should see firms innovating to reduce manufacturing costs and trying to gain market share and establish themselves as the industry leader. Since the IP required to meet the extremely low costs of manufacturing are not controlled by large established firms, smaller innovative companies have the opportunity to establish themselves as industry leaders. Price competition at the early stages of this industry may constrain ability of firms to innovate by limiting funds available to invest in R&D which may in turn slow adoption of RFID systems. This may force the smaller firms to enter into strategic partnerships and licensing agreements to generate capital for future developments. Niche competitors may target individual segments to provide custom solutions aimed at retail or transportation markets.

5.4 Chapter Summary

A detailed review of the value chain is analyzed in this chapter. The industry structure is analyzed with a discussion of the application of the double helix model of business dynamics. Potential sources of horizontal and vertical integration are also reviewed in this chapter followed by a critical analysis of potential competitive strategies for different members in the value chain using Porter's five forces framework. The industry structure presented in this chapter will lay the foundation to analyze the impact of disruptive semiconductor manufacturing technologies on the members in the value chain.

6 EMERGING MANUFACTURING TECHNIQUES

In this section we review emerging technologies for manufacturing of low cost semiconductor chips. All these techniques are in the early stages of development and the functional metrics are few generations behind integrated circuits fabricated using traditional photolithographic processes.

6.1 Nanoimprint Lithography

Nanoimprint lithography differs from the traditional semiconductor manufacturing techniques primarily due to the elimination of expensive optical lithography equipment. It resembles contact printing in a lot of respects but does not depend on physical contact between the mask and the wafer. This technique has been pioneered by researchers at Princeton University (Stephen Chou's group). Nanoimprint Lithography has been shown to be capable of printing device features less than 25 nm size with 70 nm pitch.

The mask is a 1:1 replica of the device feature size which are to be patterned and is made using E-beam. The wafer is coated with a few nano liters of resist which has a low temperature and pressure coefficient. The mask is brought in contact with the monomer layer by applying a pressure of around 400-1900 psi. The physical contact between the substrate which can be either silicon dioxide, Silicon or ceramic or metal surface is removed after an impression has been created in the resist surface. This operation is conducted in a vacuum chamber to eliminate air bubbles at elevated temperatures of 140-180 C. Once the mold is removed, the depressed resist areas can be removed using reactive ion etching using oxygen.

In order to minimize the number of molds which are required for large throughput nanoimprint lithography, it is critical to prove that the surface of the mold is not damaged through repeated imprint cycles at elevated temperatures and pressure conditions. Another potential area which requires some development is the ability to use molds which can be used for wafer level printing since this can increase throughput by orders of magnitude compared to traditional lithographic techniques which are limited to reticle level processing.

Successive application of Nanoimprint lithography has been used to fabricate multilayer resist patterns. The use of polystyrene resist in conjunction with PMMA (poly methylmethacrylate) for multiple levels along with reactive ion etching is one method. Since the top surface resist pattern is imprinted on polystyrene which has a glass temperature of 0 C compared to 93 C for PMMA, the top layer can be imprinted without causing the PMMA (lower) resist layer from flowing. Silicon dioxide is used as a barrier (dielectric) layer to separate PMMA and polystyrene.

Differential in RIE rates between polystyrene and PMMA (20 nm/min compared to 60 nm/min for PMMA) has been exploited to pattern a multilayer resist pattern by Xiaoyun et. al In addition the differences in thermal properties between Novolak resin and PMMA have been used to implement an imprint and lift off mechanism.

This process is particularly critical to low cost manufacture of RFID tags since the feature sizes and density requirements are much lower for them compared to conventional processors. The operating speed of the RFID tags is also not a critical parameter. The primary objective is the reduction of cost of high volume manufacturing by elimination of expensive optical lithography steps. One of the major issues for Nanoimprint lithography is the accuracy of alignment of multilayer patterns. For RFID tags, this is a constraint for proper fabrication of device structures but they do not have as many layers to fabricate compared to the conventional circuits and the circuit configurations can be designed to be less sensitive to variance in pattern alignment. The Nanoimprint technique pioneered by Chou et al is illustrated in Figure 16.[27] A summary of the key characteristics of the different Nanoimprint techniques demonstrated by Xiaoyun et al. is shown in Table 4.

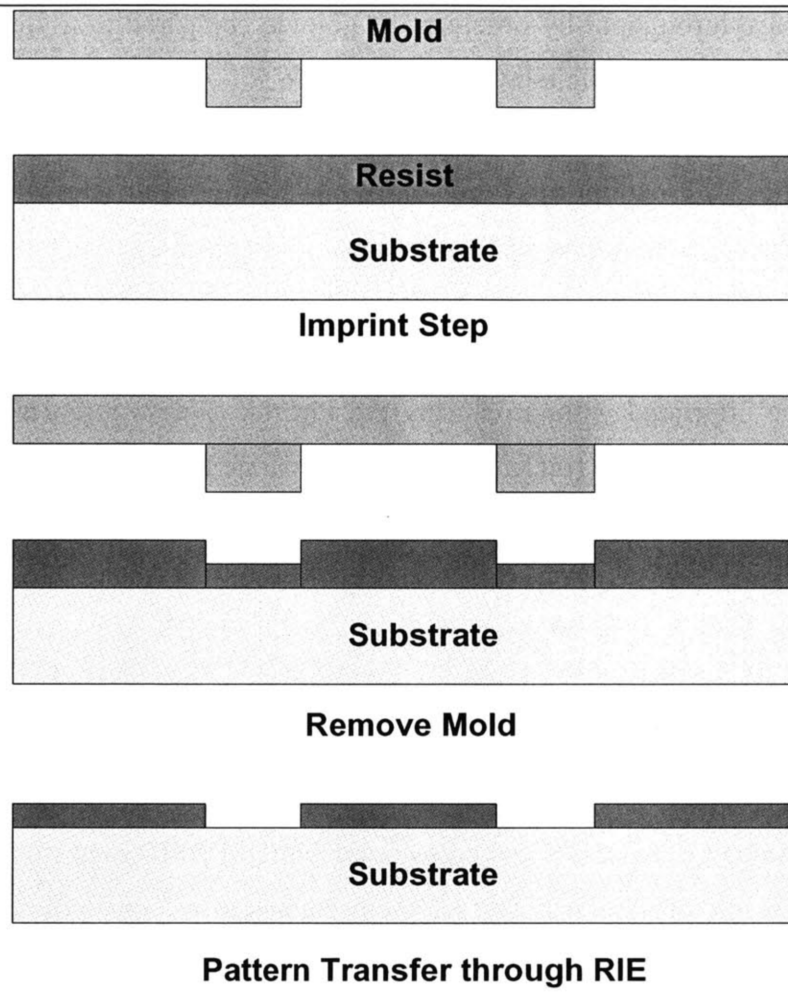

Figure 16 Nanoimprint Lithography Process

	resist layer 1	resist layer 2	resist layer 3	mechanism	critical point
Trilayer resist	PMMA	Si dioxide	Polystyrene	differential glass temperature	more processing steps, complex
Imprint and liftoff	PMMA	Novolak resin	-	differential glass temperature,Cr etching mask	careful resist material layer property matching required
Imprint and RIE scheme	PMMA	polystyrene	-	differential glass temperature, differential etching rate for RIE	careful resist material layer property matching required
Imprint and roller	PMMA	polystyrene	-	roller printing of second layer	simple but difficult to get good coverage for top surface
Imprint and etch back	PMMA	polystyrene	-	spin coating of second layer, RIE of second layer pattern to bottom layer	good planarization required for second layer resist

Table 4 Comparison of Nanoimprint techniques

6.2 Step and Flash Imprint Lithography

Step and Flash Imprint lithography is being developed to overcome the limitations of Nanoimprint lithography, namely the necessity of high pressure for imprinting and processing temperatures above the glass temperature of the resist material and the inability of high aspect ratio and pattern density. Colburn and his group at the University of Texas at Austin have demonstrated the use of SFIL to print feature sizes less than 100 nm.

The SFIL process requires the coating of a silicon substrate with an organic transfer layer. The transfer pattern can be created on a quartz template coated with chromium and resist. Standard E-beam lithography techniques accompanied by dry etching can be used to transfer the pattern.[28] The quartz template which is transparent is brought in close proximity of the silicon substrate. The gap between the template and the substrate is filled with a low viscosity photopolymerizable organosilicon solution. The gap is filled through capillary action. UV exposure cures the polymer and prints a the pattern onto the transfer layer on the substrate. RIE is used to strip the transfer layer while the cured polymer patterns act as an etch barrier. In subsequent steps the cured polymer can be etched after intermediate processing steps.

Similar to the Nanoimprint lithography technique pioneered by Stephen Chou, release agents are added to improve the ability to separate the templates from the transfer layer after UV radiation process. Using this technique features sizes down to 60 nm have been imprinted at low pressure and temperature. Unlike the Nanoimprint lithography which depends on a physical process, the SFIL process is mainly a chemical process.

For high quality imprints using SFIL, it is critical to select the properties of the material used in this fabrication technique. The release agents added to the photopolymer organosilicon is critical to ensure that the resolution of the imprints is not damaged during the liftoff process. The transfer layer needs to adhere well to both the silicon substrate and the template. In addition it should have good anisotropic etch properties to enable printing of high aspect ratio features. Another critical consideration for reproducing high aspect ratio features is the necessity of the transfer layer to have a much higher etch rate compared to the photoplolymerized etch barrier. The differential etch rate is used to remove the transfer layer once the template has been removed after the UV irradiation step to continue with further processing steps such as ion implantation to fabricate active devices.[29] The SFIL step can be repeated on subsequent layers (which are separated by a dielectric) to enable the creation of a multi-layer interconnect system. A schematic representation of the different processing steps involved in the Step and Flash Imprint lithography is shown in Figure 17.

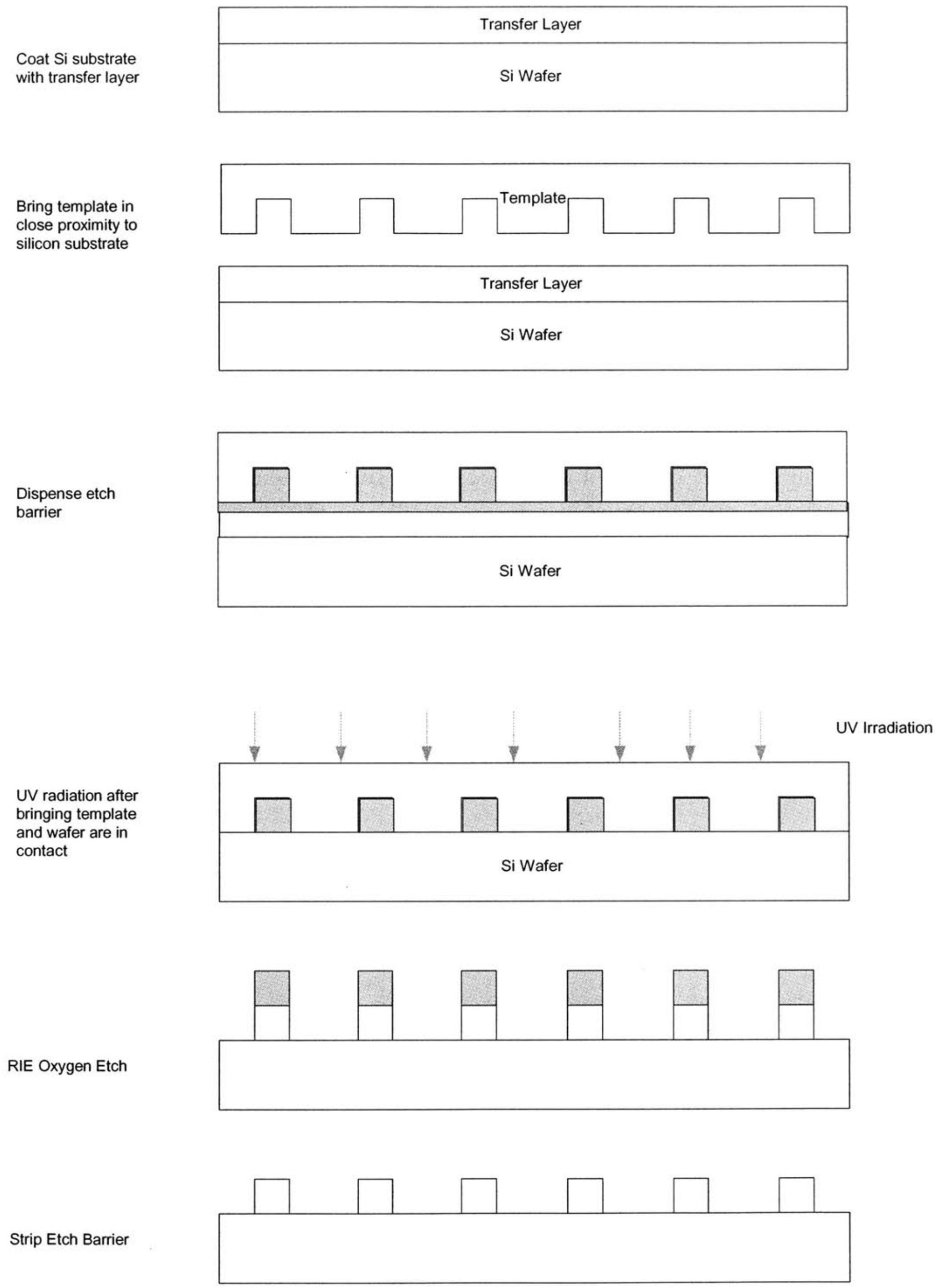

Figure 17 Step and Flash Imprint Lithography

6.3 Inkjet Printing

Inkjet printing is one of the promising approaches being pursued to reduce the cost of fabricating semiconductor circuits. Conventional lithographic techniques involve use of expensive photolithographic equipment with numerous subtractive steps for patterning. Inkjet printing offers an alternative for direct printing of the features on the substrate. Since it is mainly an additive process, it eliminates the waste of materials during the subtractive process steps. Inkjet printing process has been explored for printing active devices on organic polymers like Pentacene since it enables printing on flexible substrates using commercial off the shelf printing equipment. The throughput of the printing process can be increased using parallel nozzles and the frequency of imprinting.[30] Another advantage of the inkjet printing is the fact that no physical contact is made between the substrate and the inkjet nozzle. This eliminates the concern with deformation of molds or masks due to physical contact in the case of Nanoimprint and Step and Flash lithography. In addition, no complex chemistry is involved in the design of the mold release agent since there is no contact involved.

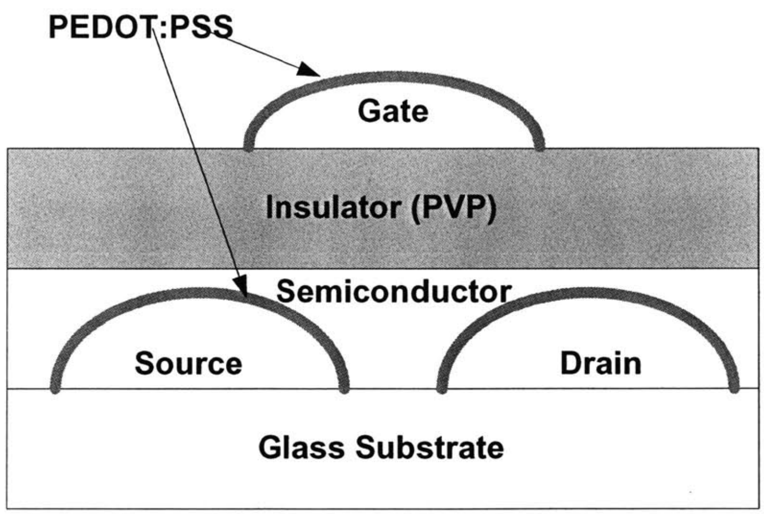

Figure 18 Structure of all-polymer TFT

The structural representation of the all polymer TFT fabricated by Kawase et al , is shown in Figure 18. The source and drain electrodes are directly printed onto the glass substrate using

PEDOT: PSS. The semiconductor, F8T2, is then spin coated and annealed in nitrogen at temperatures greater than 265 C. This is followed by spin coating of the gate insulator which in this case was polyvinylphenol. The gate electrode is then printed using inkjet print heads. Fabrication of via holes has also been demonstrated by inkjet printing of a solvent. The insulator dissolves locally and is deposited at the edges when it dries up forming crater like via holes.

TFT fabricated using this technique is still quite primitive compared to the feature sizes of conventional state of the art lithographic methods. The drain current observed in this experiment was 10 μA at a significantly high gate voltage of -40 V. Current generation device using 90 nm technology operate in the range of sub 1.2 volt supply voltage and have drain currents in saturation in the range of 1 mA/μm.

Cheong et al[31] have demonstrated the use of inkjet printing of copper metallization using an inverted configuration. The use of xerographic toner masks has been employed for etching the gate electrode and for defining the source/drain regions using a laser printer. Figure 19 illustrates the processing steps used to fabricate the copper metallization for the amorphous Si TFT. The channel length of the devices fabricated using this technique was around 90 μm.

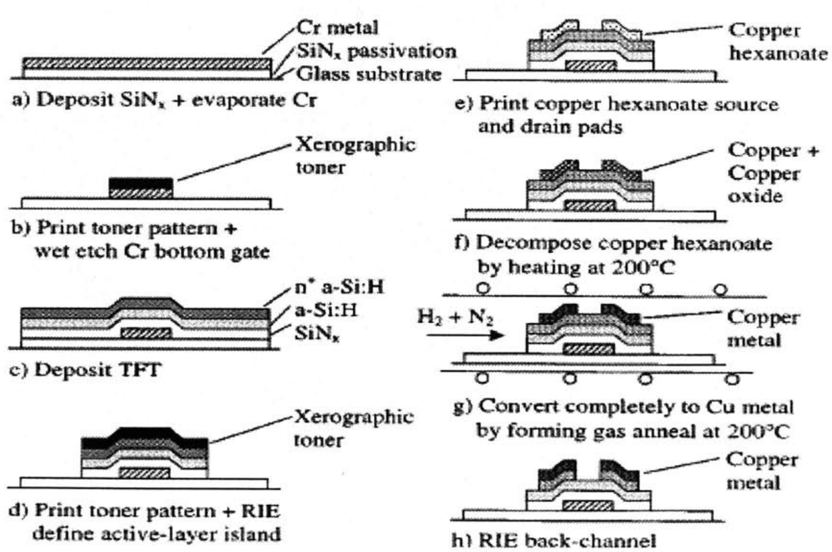

Figure 19 Inkjet printing of metallization for TFT

Another interesting application of the inkjet printing technology has been demonstrated by Redinger et al. They have fabricated passive components, namely resistors, inductors and capacitors using a Dupont ST505 Melinex film as a substrate. The resistivity was controlled by varying the thickness of the line printed. Multilayer interconnects and the dielectric layer for capacitors was realized using polyimide dielectric.[32] A summary of the materials employed and the operating conditions used is shown in Table 5.

	Material	Anneal temperature	Print temperature
Conductors	10 wt. %2 nm diameter hexanethiol encapsulated gold nanocrystal solution	130 C	160-190 C
Dielectric	Pyralin diluted P12555 polyimde	190 C	90 C
Substrate	Dupont ST 505 Melinex Film	-	-

Table 5 Operating conditions and materials used for all passive component printing

6.4 Soft Lithography

Soft lithography is a generic name for the process of fabricating patterns using an elastomeric stamp or mold onto a substrate. This technique has been pioneered by George Whitesides group at Harvard University. Elastomers are rubber like materials that are comprised of chainlike flexible organic molecules which are irregularly coiled. They have a tendency to stretch in the direction of applied force and regain their shape on removal of applied force. Self Assembly of monolayers is one of the key processes used in Soft Lithography. The substrate is usually dipped in a ligand solution or exposed to a vapor of the reactive species. SAM[3] are formed by the chemisorption of the reactive species on the surface of the substrate. The principal advantages of this process are the simplicity of the process, low defect density and good stability under ambient temperatures.[33]

[3] SAM Self Assembled Monolayer

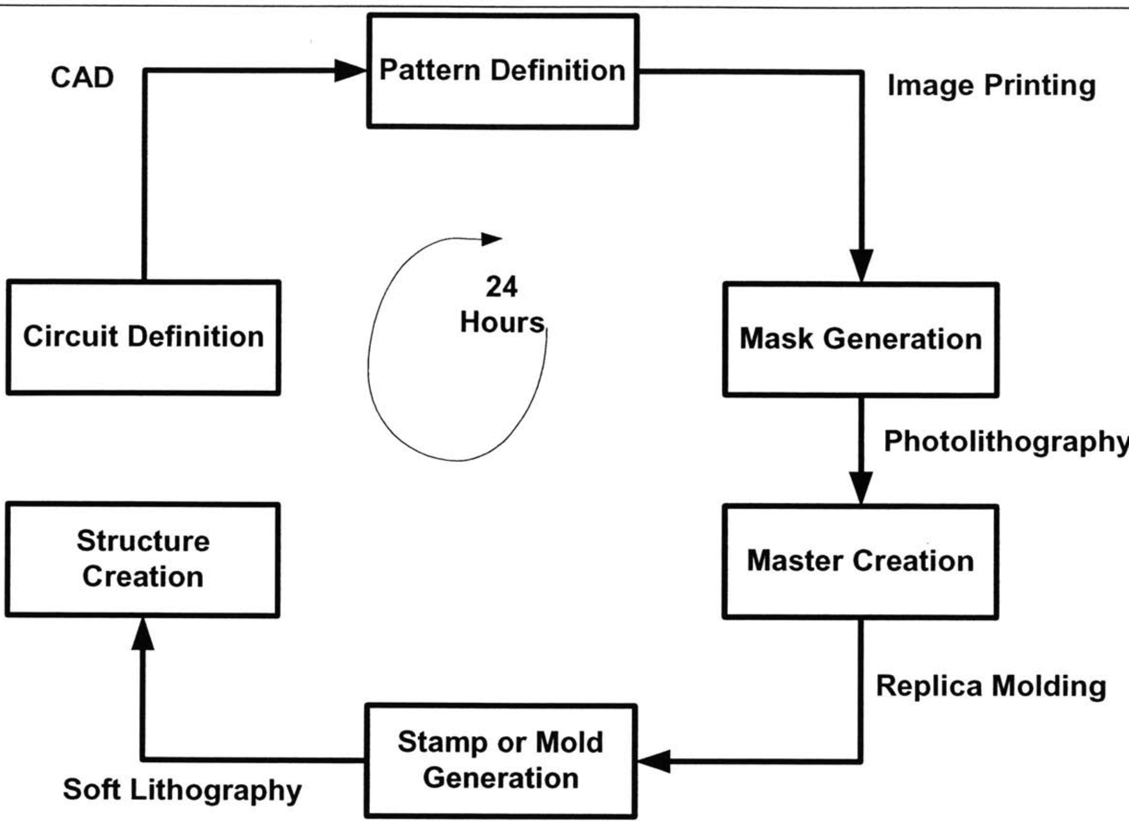

Figure 20 Soft Lithography Process [33]

As illustrated in Figure 20, the soft lithography process can be completed within a very short time without the necessity of expensive cleanroom fabrication equipment generally required for traditional semiconductor manufacturing using photo-lithography. The only step which may require photolithography is during the creation of the mask for master generation. E-beam lithography can be used for sub 100 nm feature definition.

Elastomeric molds and stamps can be created by pouring a liquid prepolymer on a master having relief features on it and curing at high temperature or exposure to UV light. PDMS (polydimethysiloxane) has been used by Whitesides et al since it is chemically inert, optically transparent till 300 nm, deformable to ensure contact over non flat surfaces and conforms to a surface over large surface area.[33] Figure 21 illustrates the preparation of an elastomeric mold using PDMS prepolymer.

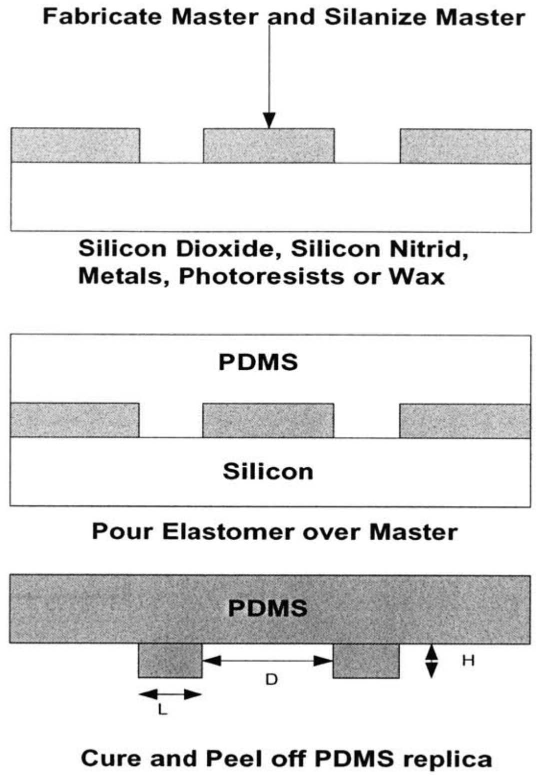

Figure 21 Preparation of Elastomeric Mold

6.4.1 Microcontact Printing

Microcontact printing is one technique which is used to self assembled monolayers by using a PDMS stamp dipped in an ink. The stamp is brought in contact with the substrate and the ink molecules are transferred to the substrate surface.[34] The self assembled monolayer can be used as an etchant mask for further processing steps like ion implantation for fabrication of active devices or for growing a different self assembled monolayer in regions not exposed by the micro contact process step. Figure 22 illustrates microcontact printing of self assembled monolayer using an elastomeric stamp. Microcontact printing has been extended to a fast throughput process by the use of a rolling stamp with features which are dipped in ink of the material whose self assembled monolayer is to be deposited on the substrate.[35]

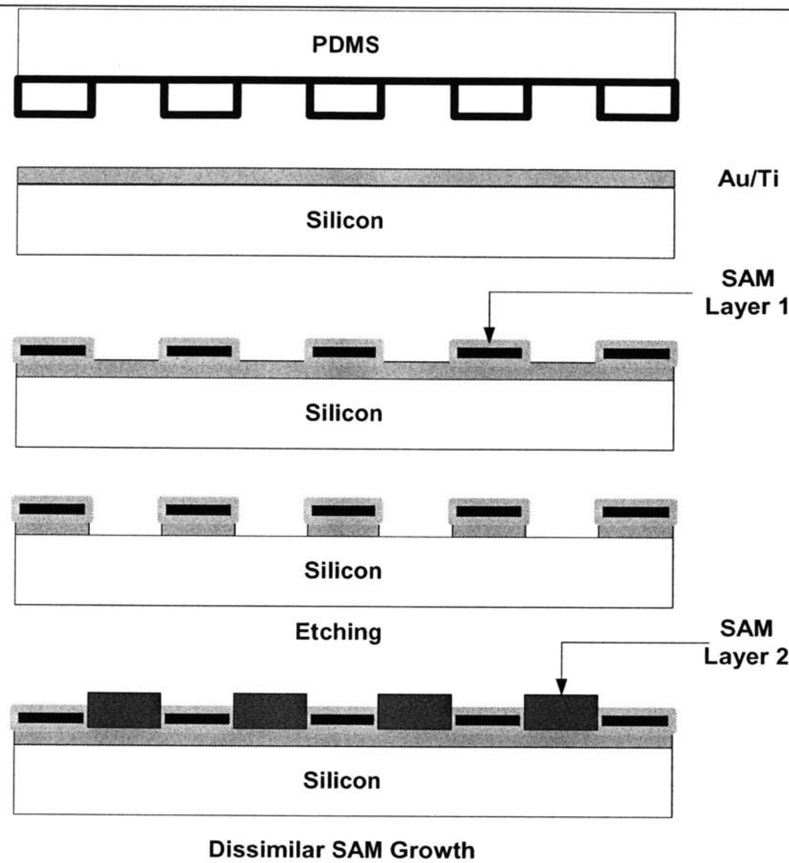

Figure 22 Microcontact Printing of Self Assembled Monolayer

6.4.2 Micromolding

Another technique pioneered by Whiteside et al, is Micromolding. There are variations of this scheme but all of them depend on utilizing PDMS to create a feature definition on a substrate. The four main variations of Micromolding are listed below:

1. Replica molding
2. Micro transfer molding
3. Micro molding in capillaries
4. Solvent assisted micro molding

In case of replica molding the prepolymer is poured onto a PDMS substrate with relief features and cured. The flexible replica created is then removed. In case of microtransfer molding, the prepolymer is poured onto a PDMS substrate with pattern defined on it. It is then placed on a substrate and cured. The residual film is then transferred onto the substrate when the PDMS mold is removed. Micro molding in capillaries involves using a PDMS mold but the difference lies in the use of capillary action to fill the channels created by the PDMS mold and the substrate. After curing, when the mold is removed, the relief features are imprinted onto the substrate. In case of solvent assisted micro molding, the PDMS mold is dipped in a wetting solvent and placed on a substrate which has a polymer film coated on it. When the solvent is evaporated with the PDMS mold in contact with the substrate, the features are imprinted on the polymer film due to dissolution of the polymer film on evaporation of the solvent.

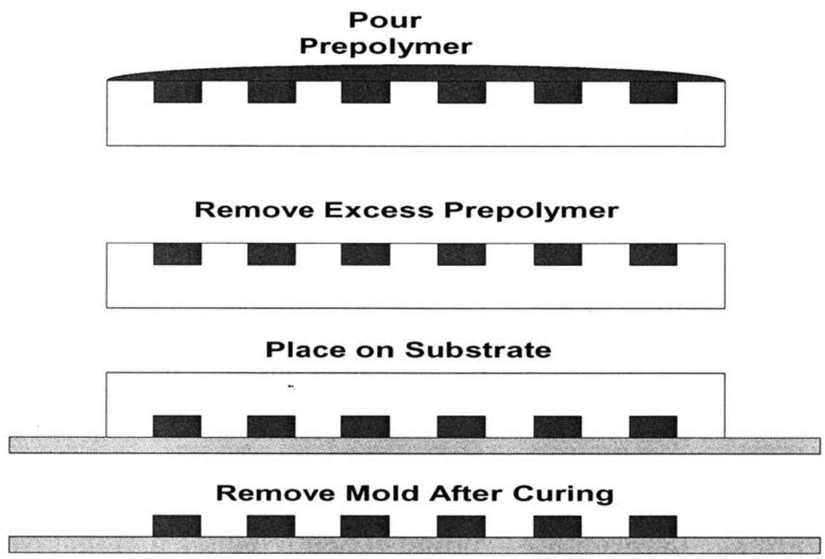

Figure 23 Microtransfer Molding

6.5 Spherical Integrated Circuit Processing

Spherical integrated circuit processing is a radical innovation involving the processing of miniature polycrystalline silicon granules into single crystal silicon balls. Instead of processing circuit features on individual dies on a planar wafer surface, Ball Semiconductor has developed a process to directly perform operations like cleaning, drying, grinding, coating and etching. These operations are performed within enclosed hermetically sealed pipes and do not need expensive cleanroom facilities. The spherical surface provides a means of fabricating a more efficient antenna by patterning winding around the surface. Since antenna fabrication and patterning can be done on single silicon crystals, the expensive processing steps involving wafer dicing and pick and place assembly can be completely eliminated. This approach is in its infancy and will take significant research and development before large scale integrated circuits can be proven to work. This approach needs to mature to be able to utilize it to pattern RFID circuits on spherical surface but the potential for low cost of fabrication is present. Another approach would be to integrate soft lithography techniques using an elastomeric stamp which can conform to the curved surface. The constraining factor would be the size of the individual spheres which can be patterned efficiently using this approach. Figure 24 illustrates an example of an integrated circuit fabricated by Ball semiconductor on a spherical surface.

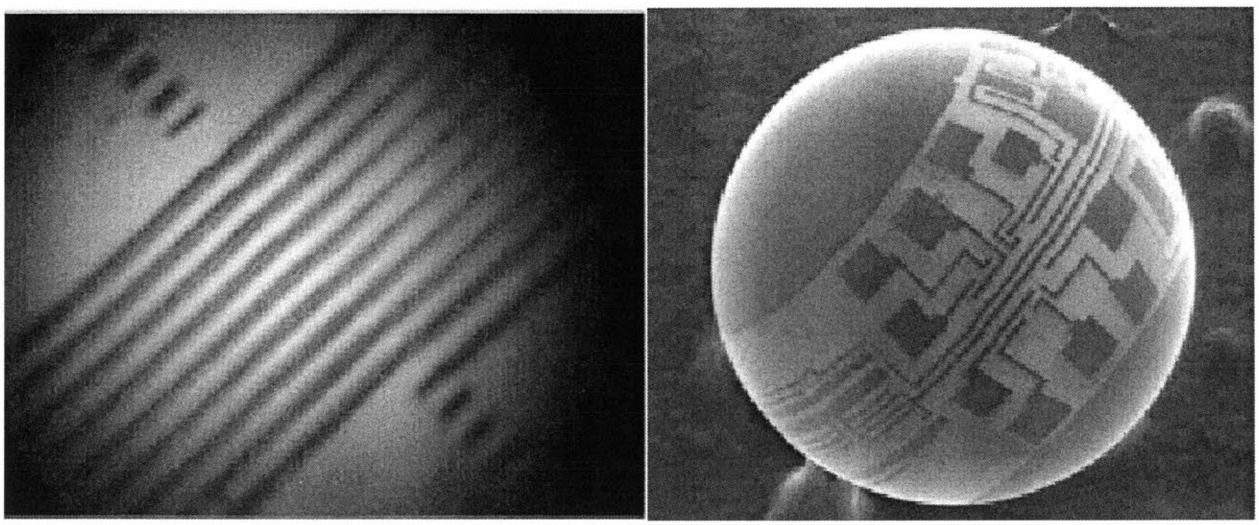

Figure 24 Spherical Integrated Circuit[36]

6.6 Chapter Summary

This chapter analyzes five disruptive semiconductor manufacturing techniques which are in early stages of development. Nanoimprint, SFIL, Inkjet Printing, Soft Lithography and Spherical Integrated Circuit Processing have the capabilities to be used for RFID tag manufacturing. All the methods avoid the use of optical lithographic processes for high volume manufacturing except for patterning the template masks or molds. This is critical to reducing the cost of manufacturing. Another key observation is the complex engineering of material chemistry for enabling high density sub 100 nm scale feature sizes. At the current time none of the methods have been used to pattern integrated circuits with device parameters which are even close to current generation devices in terms of switching speed or density. Significant research and development work is needed before multilayer integrated processes can be developed to enable fabrication of integrated circuits which can be used for manufacture of RFID tags.

7 PACKAGING AND ASSEMBLY

7.1 Conventional Assembly

In traditional semiconductor manufacturing the wafer is first tested to identify functional dies and also to mark them based on frequency of operation. The wafer is then subjected to backgrinding using a chemical-mechanical process. It is then mounted on a mylar adhesive tape. A laser scribe is used to cut a trench in the ILD[4] layer along the scribe lines and this is followed by a sawing process with a diamond tool to separate the die. This is illustrated in Figure 25.

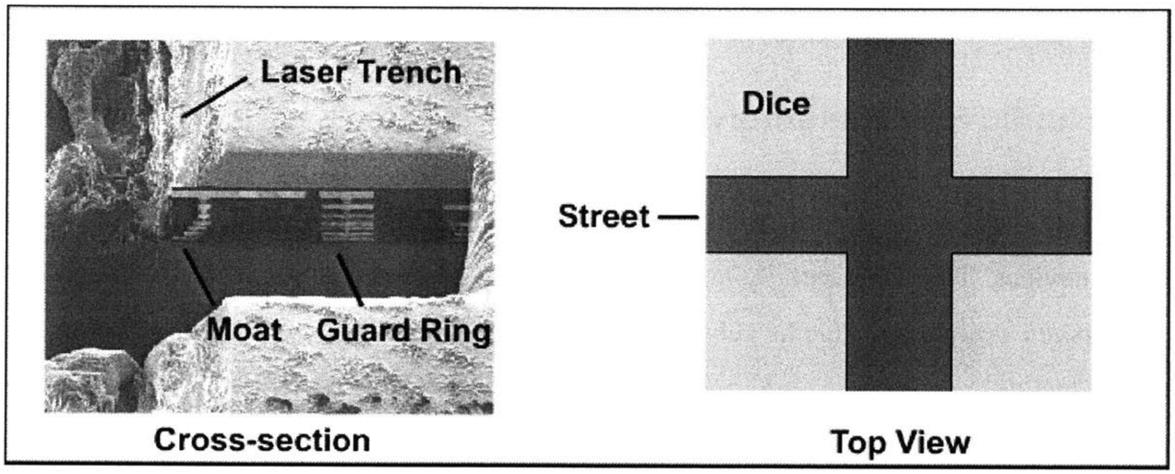

Figure 25 Laser Scribe Process (Source: Intel)

A robotic pick and place tool is used to separate the functional dies from the mylar mount and place them on tape carriers. This is illustrated in Figure 26. In the case of RFID tags, the die size is extremely small (500 square microns) compared to microprocessor or other logic chips. The robotic pick and place process does not lend itself to the manufacture of RFID tags since even a slight misalignment can cause stacking up of dies. The throughput achievable through this process is also limited. An additional constraint is the line width of the scribe lines which can be etched using a laser tool and diamond saw. Alternative approaches using wafer back side thinning and Reactive Ion Etching have been reported to produce scribe lines which are less than 5 μm in width.[37]

---

[4] ILD Inter Layer Dielectric

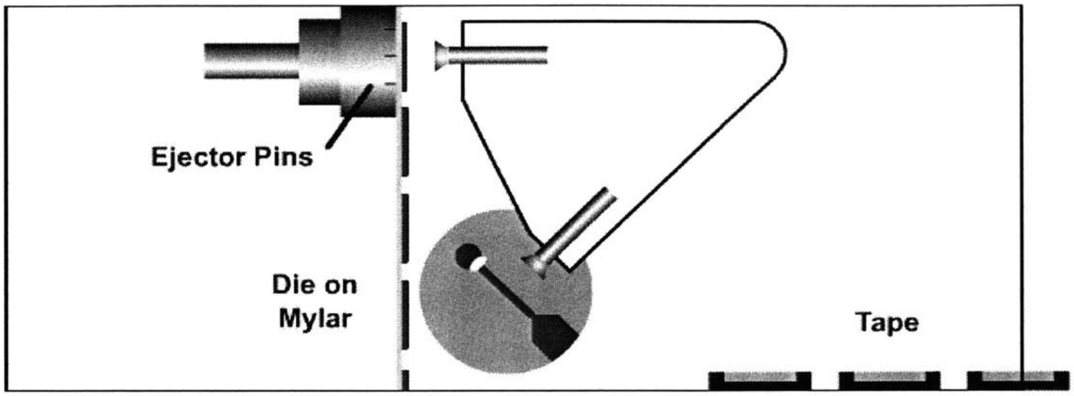

Figure 26 Robotic pick and place tool (Source: Intel)

7.2 Fluidic Self Assembly

Fluidic self assembly of microstructures has been pioneered to enable the integration of dissimilar devices. This was initially targeted for the optoelectronic integration since the optical components are designed on GaAs substrates and electronic devices are fabricated using silicon processing technology. Yeh et al demonstrated the integration of microstructures using a fluidic carrier for integration of GaAs light emitting diodes on microwave silicon devices.[38] The primary advantages of this approach are:

1. Processing of GaAs and Si devices can be done independently and in parallel
2. Integration on the host Si substrate is a self aligned process
3. Assembly is a batch process done in an inert fluidic medium

Since this assembly process obviates the need for an automated pick and place process and scales well independent of the size of the microstructures, it can be utilized for the assembly of RFID tags as well. These characteristics have motivated Verma et al[6] to apply it for the assembly of RFID tags. The technique used by Yeh et al is shown in Figure 27.

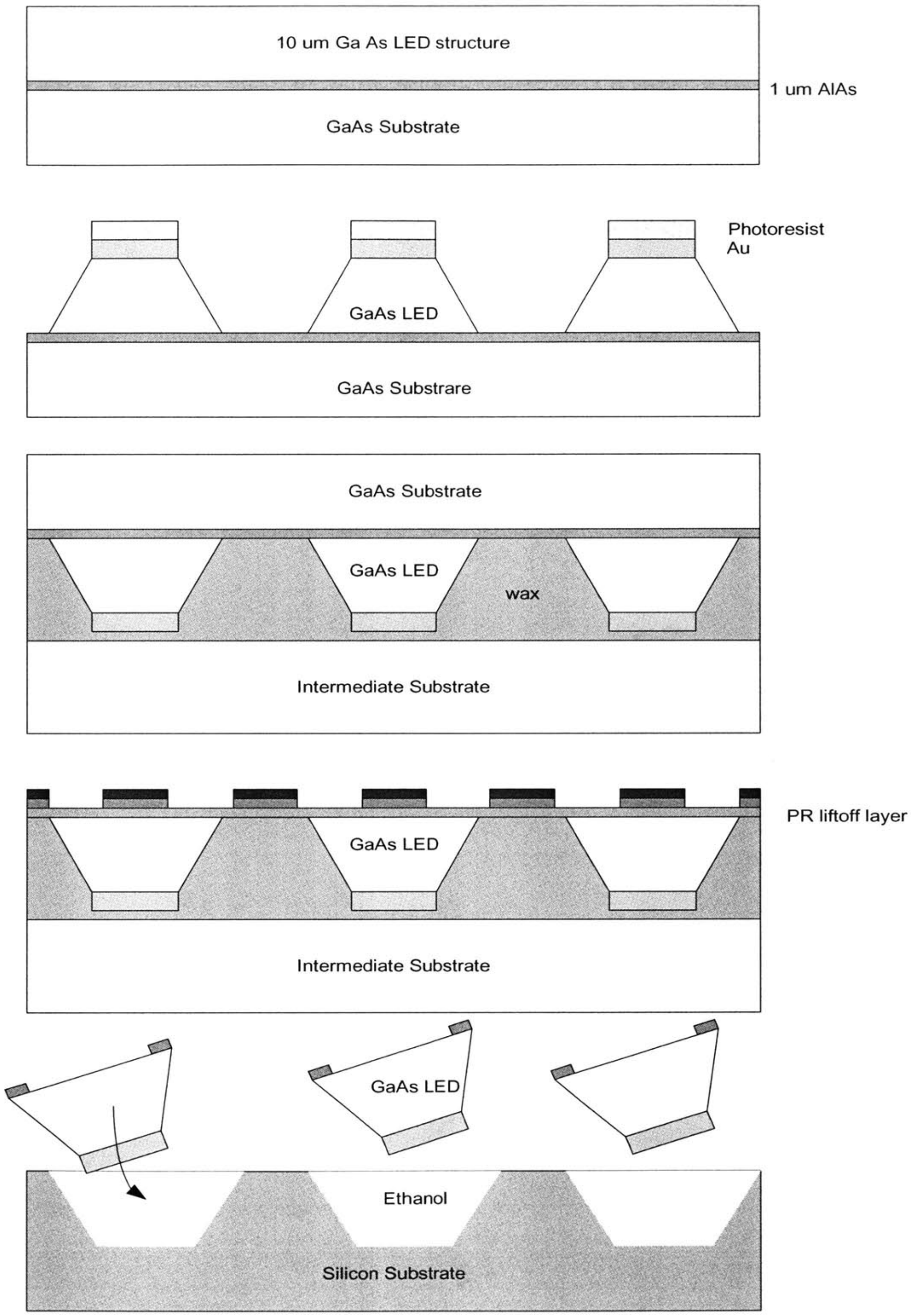

Figure 27 Fluidic Self Assembly of GaAs LED on Silicon Substrate

GaAs LED structures are first fabricated on a GaAs wafer. A trapezoidal structure is then realized through ion milling. After intermediate processing steps and addition of metallization contacts to the LED devices, the trapezoidal shapes are separated by dissolving the wax and the LED structures are placed in a carrier fluid (ethanol) which has the Si substrate which have identical but slightly larger trapezoidal shapes. The patterns are created using anisotropic etching of silicon dioxide. The preferential etching sensitivity (slower) along the {111} plane created the slanting edges. When the GaAs LED devices are floated in an ethanol medium which has the silicon substrate immersed in it, the LED are assembled in the locations defined by the trapezoidal holes in the silicon substrate.[38]

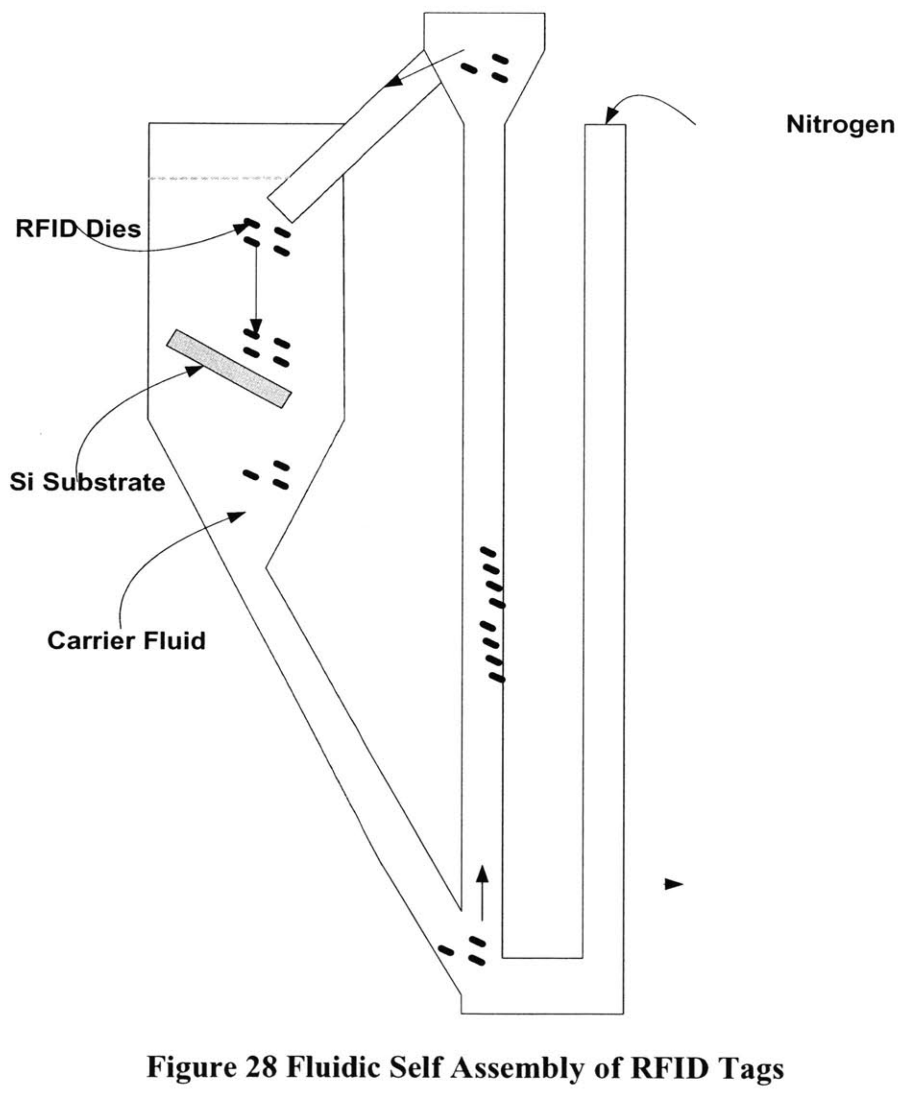

Figure 28 Fluidic Self Assembly of RFID Tags

Verma et al have used fluidic self assembly for RFID tag integration to a silicon substrate in a methanol carrier medium. They have used a nitrogen recirculating bath to recirculate the dies so that they are reused to fill any unused holes in the silicon substrate. The experimental setup used to demonstrate this process is illustrated in Figure 28.

The efficiency of filling the substrate holes can be increased by increasing the surface friction on the substrate so that the small dies do not aggregate on the substrate thereby blocking the remaining dies in the carrier fluid from filling unoccupied slots in the substrate. A low frequency agitation was also utilized to improve the filling efficiency without causing turbulent flow in the carrier medium since this has a tendency to dislodge the filled holes in the substrate.

7.3 Paper on Chip Assembly

Another low cost method of RFID tag assembly is the use of Chip on Paper technology using anisotropic conductive adhesive.[39] It has been pioneered by Motorola Inc. for RFID tag manufacturing. This application lends itself to high volume, low cost manufacturing since it can be adapted to roll on roll manufacturing. Anisotropic conductive adhesive (ACA) is coated on a paper substrate. Since the conductivity is significantly greater in the axis perpendicular to the die, electrical contact can be made by using an unbumped flip chip. The antenna is printed on the paper substrate using carbon conductive ink. The flip chip is assembled onto the paper substrate coated with ACF under thermal pressure. Low temperature is used since the substrate used is paper based. A critical factor in selecting the composition of the ACF is the solid Nickel spheres should have a diameter significantly less than the separation between the die and the substrate or else there will be an electrical short. A cross section of the Chip on Paper RFID tag assembly is shown in Figure 29.

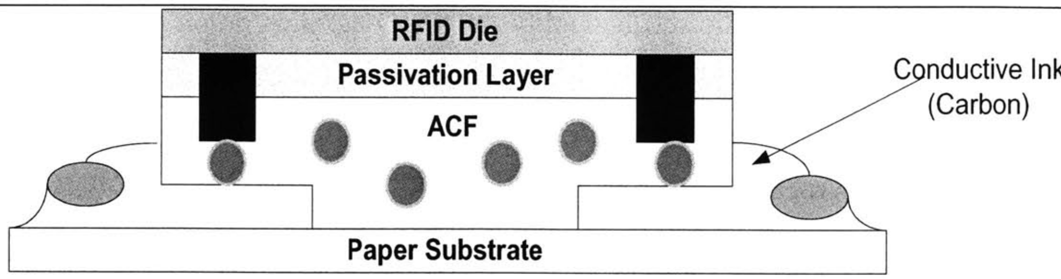

Figure 29 Chip on Paper Assembled RFID Tag

A potential extension of this technique would be to integrate a odor sensor using the technology developed by Cyrano Sciences which relies on using the change in electrical conductivity of conductive thin film carbon composite polymer array of chemiresistors.[40] The electronic nose developed by Cyrano Sciences relies on the change in electrical conductive of conductive carbon polymer due to the diffusion of odor particles. The conductivity change signature profile is compared to a library to identify known chemicals. This process lends itself to easy integration with the paper on chip assembly process.

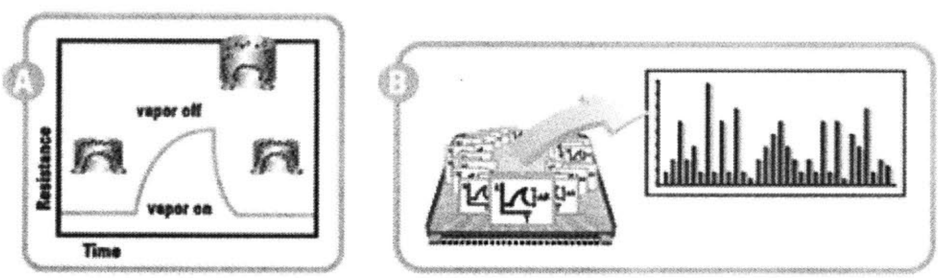

Figure 1. A) A representation of the composite detector material responding during an analyte exposure. B) A representation of how data are converted into response patterns.

Figure 30 Cyrano Sciences Electronic Smell Sensor[40]

7.4 Vibratory Self Assembly

Another approach which was developed at MIT is vibratory self assembly. A low frequency vibration is used to feed the RFID tags and they are aligned using detents and transferred on to rolls of substrate material.[5] An example of the apparatus developed by Phillips Semiconductor is illustrated in Figure 31.

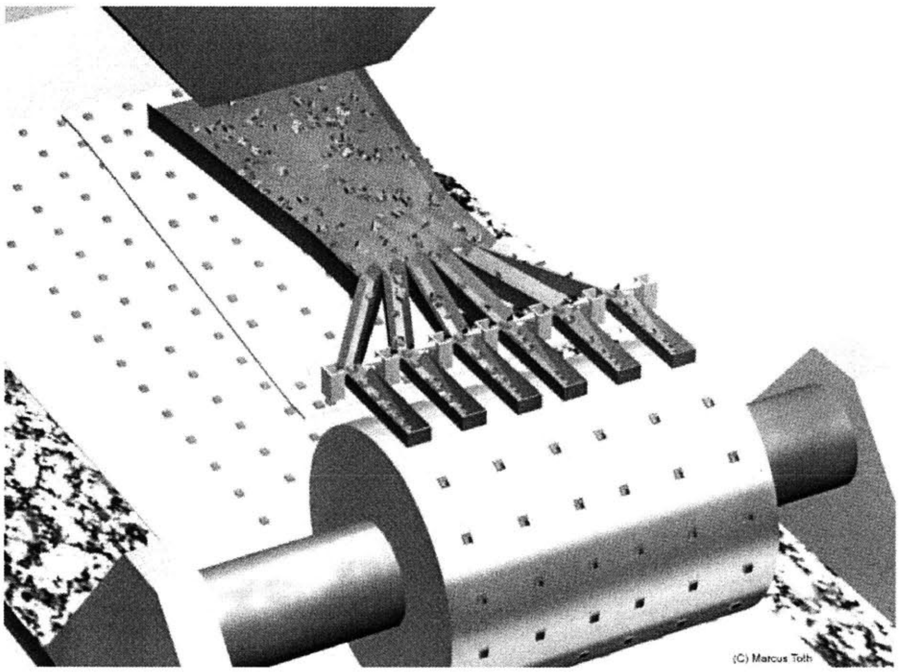

Figure 31 Vibratory Assembly of RFID Tags (Source: Phillips Semiconductor)

7.5 Parallel Integrated Circuit Assembly

The traditional semiconductor chip assembly process relies on sequential pick and place assembly techniques. This process does not lend itself to low cost of manufacturing as shown in Figure 32. Assuming a per tag pick and place duration of 13 seconds and cost per individual robotic pick and place machine to be $1.5 million, we can easily see the difficultly of reaching cost targets for the assembly process just considering the capital cost amortization over the life cycle of the robot. This simple analysis does not even consider the changeover times. Since the RFID dies are minute (500 um x 500 um), it is critical to explore parallel processes which can accomplish the assembly process with a much higher throughput. Matrics Inc. has taken an innovative approach to address this challenge. They have developed the PICA-Parallel Integrated Circuit Assembly process to accomplish the assembly operation.

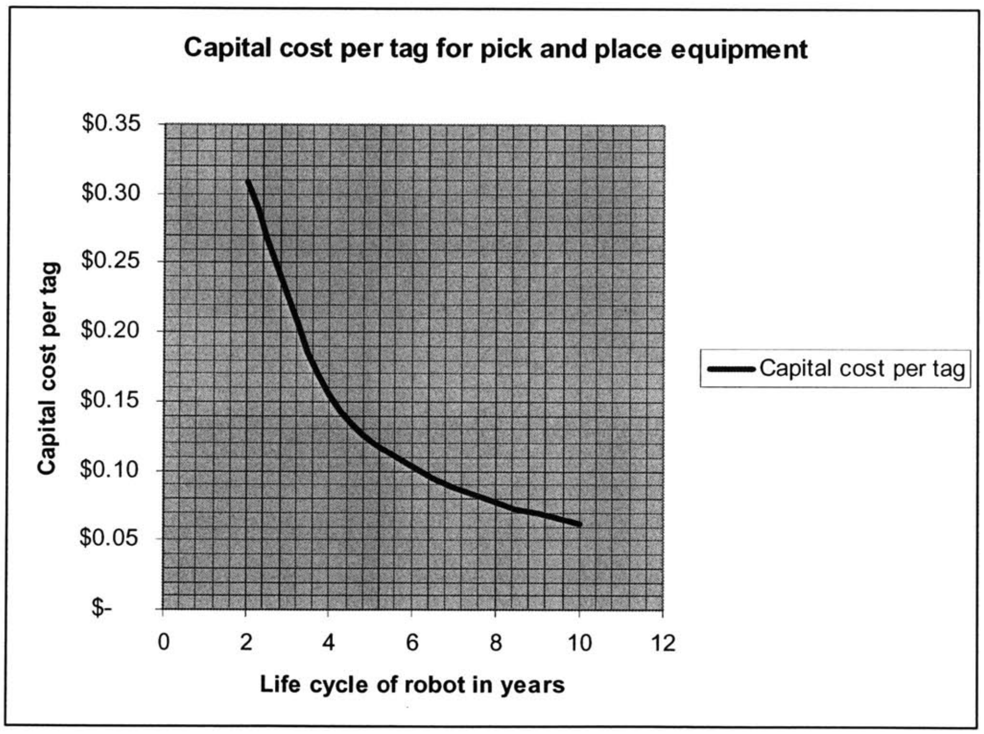

Figure 32 Estimated cost scaling of sequential pick and place process

The PICA process developed by Matrics Inc. relies on two key principles:

1. Special adhesive used for attaching die to substrate which is cured in a short time using UV exposure
2. Parallel operation to pick multiple dies from the wafer to attach to the substrate

The wafer is attached to a backing plate and moved under a pin plate with multiple pin shaped dispensers. These pins are prepositioned to the pitch of the antennas. The UV curing adhesive is released and UV light is flashed to attach the die to the antenna substrate. The curing occurs in 1/10th of a second. The wafer is then repositioned to attach the next set of dies. Matrics Inc. estimates that it will be able to reach throughput of 30 million tags/hour per machine. The expected cost per machine is less than $1 million. A schematic illustration of the PICA process is shown in Figure 33.

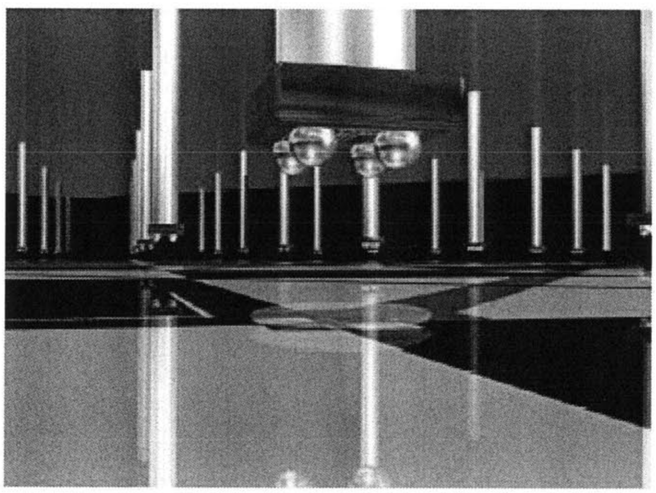

Figure 33 PICA Process Equipment[41]

7.6 Chapter Summary

This chapter examines the two key constraints of traditional assembly processes which limit high volume low cost production of miniature RFID dies. The limitation of scribe line width result in wasted silicon wafer area during the dicing process. In addition, the scaling of robotic pick and place robotic machinery for assembly of RFID dies limit cost reduction. Innovations in fluidic self assembly process, vibratory assembly, paper on chip substrate and parallel integrated circuit assembly are analyzed for applicability to RFID manufacturing. All these methods are capable of high volume assembly with significant cost reductions compared to traditional semiconductor processes. Paper on chip substrate assembly method has an interesting application which could be explored for the integration of odor sensors along with the tags. Another point to note is the wider scope of application of these methods to additional semiconductor applications which involve assembly of miniature dies on a substrate like liquid crystal on silicon displays or integration of optoelectronic devices.

8 SECURITY ISSUES FOR RFID SYSTEMS

8.1 Security Concerns

"There is more information available at our fingertips during a walk in the woods than in any computer system, yet people find a walk among trees relaxing and computers frustrating. Machines that fit the human environment, instead of forcing humans to enter theirs, will make using a computer as refreshing as taking a walk in the woods."[42]

The prophetic words of Mark Weiser in relation to the prediction of proactive and ubiquitous computing are all the more relevant in recent times with the advances in technology in the field of RFID systems and low cost wireless networks. With the opportunity for reduction in the cost of manufacturing RFID tags below the $ 0.05 threshold, the ubiquitous deployment of RFID based tracking systems everywhere no longer seems a distant reality. With every new development in science and technology, there are instances of it being used to do more harm than good. RFID based computing and communication systems herald the promise of enabling pervasive computing at low cost and thereby enable significant efficiencies in the manufacturing and logistics in the supply chain, in addition to reducing the operational expenses in all industry segments.

At the same time, tracking of consumer goods using RFID tags can also be seen as a mechanism to invade on the privacy of consumers. Another example of RFID tags raising the security concerns is the recent plans by European Currency Board to embed RFID tags in currency notes by 2005.[43] Since the RFID tags are passive elements, it is possible to read the contents of individual's possessions by bringing a reader in close proximity of the currency notes. This leads to the possibility of identifying people with possession of high value currency with the subsequent implication on increase in targeted thefts. One of the applications proposed in the retail industry is the tagging of individual items by embedding RFID tags in the packaging of

Individual items. This will enable real time updates of inventory in the retail warehouses and stores. This can lead to implementation of JIT supply replenishment which can reduce the inventory costs for the retail industry. In addition, it is possible to keep track of the inventory with much fewer personnel since the RFID tags can be read in a multiplexed manner through smart shelves which have embedded readers with wireless communication capabilities. This has significant impact on the operational expenses of large retail chains.

Another potential application of the RFID tags is the automated billing of the shopping cart along with payment processing using the information stored in the RFID tags of items in the shopping cart and the use of smart cards equipped with similar technology for payment processing. This has the potential of improving the customer experience by elimination of waiting time at checkout counters but at the same time can lead to elimination of jobs associated with checkout counters. A trend along these lines is already visible at some retailers like Fred Meyer which have installed self-service pilot lines which enable customers to scan the bar codes and use debit cards to pay unassisted by store personnel.

A subsequent modification of this system would be to transition to a RFID based system to improve the customer experience and save operating expenses for the stores at the cost of elimination of jobs. A drawback of this system would be the potential for unauthorized readers to be able to scan the contents of a shopping cart to identify the value and identity of contents within the cart leading to potential for thefts.

PROTEST ENSUED when the British supermarket chain Tesco began testing RFID technology.

Figure 34 Security Concerns related to RFID deployment in retail industry[14]

Recently Walmart made an announcement to require its top 100 suppliers to start tagging their deliveries to Walmart at the pallet level with RFID tags. At the same time, in mid 2003 Walmart canceled pilot trials of RFID based systems in cooperation with Procter & Gamble at a Walmart store in Broken Arrow, Oklahoma. Privacy concerns incited by media reports of consumers subjected to trial participants unknowingly led to a severe negative reaction and prompted canceling of these pilot trials. Benetton, an international clothing manufacturer suspended store pilot trials of RFID based systems in its 5000 stores and warehouses due to privacy concerns over consumer profiling using RFID tag based systems.

As seen from the above cases, for widespread acceptance of the RFID based tracking systems in the consumer products supply chain, it is critical to address concerns related to security and privacy of the consumers. In the next section, we will examine the current proposals to address the privacy concerns associated with RFID based tracking systems.

8.2 Proximity Considerations for RFID Security

Since most of the low cost RFID tags are passive elements, they derive the power for transmitting the stored information via capacitive, electrical or electromagnetic coupling. For high frequency RF tags which rely on inductive coupling for transferring power to the RFID tags, the transmitted power from the reader to the tag is inversely proportional to the cube of the separation between the reader and the tag. For UHF RFID tags, the transferred power is inversely proportional to the cube of the separation between the reader and the tag.

Inductive Coupling (HF) $P_{tag}\ \alpha\ 1/d^3$

Electromagnetic Coupling (UHF) $P_{tag}\ \alpha\ 1/d^3$

US regulations also require that RFID systems operating in the UHF bands, change frequency of transmission every 400 ms. This places a constraint on the system to complete data readouts from the tags within this time period. Based on the proximity constraints and frequency hopping requirement, security policies for RFID systems can be implemented which address the privacy considerations. Another factor to consider is that UHF signals are shielded by conductive materials.

$Đ = \sqrt{(2*\rho/(2*\Pi*f*\mu_0))}$

$\mu_0 = 4 *\Pi*10^{-7}$ H/m

$\rho = 2.65*10^{-6}$ ohm-cm for Aluminum

$\rho = 10^{-2}$ ohm-cm for saline solution

As observed from the above equation, the skin depth is inversely proportional to the square root of the frequency of transmission. At the higher frequency ranges, the depth to which the UHF signal penetrates a conductive material decreases.

8.3 Security Protocols for RFID Systems

In view of privacy concerns, Garfinkel[44] has proposed a RFID Bill of Rights for the consumer. The salient points of this voluntary mechanism are:

- Identification of items which possess RFID tags
- Deactivation of tags at point of purchase
- Consumer access to data stored on tag
- Right to access services without mandatory use of tags
- Right to know when, where and why the RFID tag data is accessed

For unauthorized access to information stored in the tags, the spurious readers need to be in close proximity and for extended duration to be able to decode the information transmitted by the RFID tags. Based on this key concept, various security protocols have been proposed. The Auto-ID center has advocated the placement of RFID tags in visible locations on consumer products so that they can be discarded easily at the point of purchase similar to existing security mechanism on retail products which are programmed to alert stores in event of theft. This may not be a viable solution with all forms of RFID tags. The BiStatix chip developed by Motorola in collaboration with International Paper will be incorporated into "smart cardboard" used as the packaging material.[45]

Another proposed solution is the functionality of a kill command which can be activated by the consumer at any point thereby disabling the transmission capability of the RFID transponder when interrogated by a reader. This would be a self-destruct mechanism which would make the tag inactive. This would not be a viable solution in case of RFID tags embedded in currency notes with the intent of eliminating forgery since the tags need to be accessible at all times to check for authenticity.

One approach to RFID tag security is to enable the tag to output a pair {r, PRNG(r,ID)} where r is a counter and ID is the secret tag identifier.[46] This scheme depends on the ability of the tag to compute a pseudo random number and relies on the reader to decipher the tag ID using an exhaustive lookup. Another scheme proposed by Sarma et al.[47] incorporates a memory stack to store a meta-ID. The tag can be in either active or locked state. The owner stores a hash value of a random key in the meta-ID location. To unlock the tag, the lock key is sent by the owner to the tag. The hash value of the key is compared with the value stored in the mea-ID location. The tag is unlocked if it matches the value stored in this location.

Alternatively, Pseudonym throttling, has been proposed by Ari Juels as an effective means of implementing RFID security mechanism.[48] The tag stores a random list of identifies known as Pseudonyms which are known a priori by authentic readers. The rate of transmission of the pseudonyms can be controlled to limit the frequency of interrogation by spurious readers. This capitalizes on the fact that illegal readers will be limited in terms of the time window they will have to access the tags. The proposed scheme relies on the reader to transmit an authentication key (b_i) on receiving a key from the tag (a_i). Only if the reader key is matched with the initial pseudonym transmitted by the tag, the tag will subsequently transmit an authentication key (c_{in}). The keys are refreshed during prior interrogation sessions. This prevents the illegal access to RFID tag information by intermittent attacks by spurious readers.

8.4 Chapter Summary

In this chapter security and privacy concerns related to the use of RFID tags for inventory tracking is reviewed. Proximity considerations which can be used in the design of RFID based inventory management systems are discussed. In order for RFID to find wider acceptance to replace barcodes to track items in the supply chain, cost parity with barcodes is not sufficient. Human factors consideration with implementation of RFID based tracking mechanisms along with addition of functionality within the tags to address security and privacy concerns is needed. This still remains an unresolved issue and will impede wider adoption of RFID as a replacement of barcodes for inventory tracking.

9 CONCLUSIONS

9.1 Research Focus

This research explores the benefits of RFID based inventory management systems and analyzes the cost drivers for low cost RFID manufacturing. Detailed system architecture decomposition is reviewed and future enhancements to the tag architecture with respect to integration of smart sensors are proposed. In addition, the functional parameters of different classes of RFID tags are compared along with applications which have the potential to drive infrastructure growth in the communications and computer industry.

9.2 Industry Dynamics

A value chain analysis of the RFID industry is presented and is analyzed from the perspective of product and process innovation. Viewed through the lens of dynamics of innovation model developed by Professor Utterback, it is evident that the RFID industry is transitioning from the fluid phase to the transitional phase with a significant increase in the number of firms entering the industry in all segments. The development of the EPC standard by the Auto-ID center may signal the establishment of a dominant design and the focus of innovation is shifting towards process innovation to reduce the cost of RFID tags.

A key issue which emerged through the surveys in the business press and discussions with key technologists is the importance of addressing security and privacy concerns. Failure to address this in a robust manner may impede acceptance of RFID based applications. Another outcome of this issue is the potential of increase in logic complexity in the RFID tags which will increase die size and cost. Hence, there is a need for further research in developing semiconductor processing techniques which will scale with the complexity increase in the RFID tags.

The industry structure is also reviewed using the double helix business model developed by Professor Fine to predict the potential scenarios for vertical integration and horizontal disintegration with establishment of standards. Potential competitive strategies for incumbents and new entrants in the RFID industry are discussed using Porter's five forces framework.

9.3 Disruptive Technologies for RFID Manufacturing

The key semiconductor processing technologies which are currently under development which may be applicable for RFID manufacturing in the future are:

1. Nanoimprint Lithography
2. Step and Flash Imprint Lithography
3. Inkjet Printing
4. Soft Lithography

All of them have the potential for low cost and high throughput manufacturing. The cost reduction is achieved mainly through the elimination of expensive optical lithography equipment for all steps except in some cases for fabrication of master templates or molds. Step and Flash Imprint Lithography overcomes the requirements of high temperature, high pressure physical process used in Nanoimprint Lithography by using UV exposure for feature definition. Both these methods require careful engineering of materials used to improve the process capabilities. One critical area is the design of mold release agents to enable accurate feature definition without damage to the mask template. Though these techniques have been used to imprint features less than 90 nm with regular patterns, the key challenge will be to develop a mature process which can fabricate circuit features which have multiple layers, non-planar surfaces and non-uniform density of patterns.

Inkjet Printing is a novel application of a mature technology for printing integrated circuits on flexible substrate. Unlike Nanoimprint and Step and Flash Lithography, it is an additive process and does not require physical contact with mask templates and substrate. Significant development need to be undertaken to prove the viability of multi-layer interconnect system and device feature sizes which are capable of reasonable switching speeds.

Soft Lithography relies on the use of an elastomeric mold and the creation of self assembled monolayers (SAM). The SAM is used as an etchant mask similar to traditional semiconductor processes. This has the capability of patterning over non-flat surfaces which are present in integrated circuits with a multi-layer interconnect system.

Technology	Cost	Traditional Performance	Ancillary Performance
Christensen's Disruptive Technology	Lower compared to incumbent technology	Lower compared to incumbent technology	Higher compared to incumbent technology
Optical Lithography based semiconductor manufacturing	Incumbent	Incumbent	Incumbent
Nanoimprint Lithography	Lower cost due to elimination of optical lithography equipment	Greater integration density, lower control over variation for multi-layer system compared to incumbent	Higher throughput, large area patterning capability
Step and Flash Imprint Lithography	Lower cost due to elimination of optical lithography equipment	Greater integration density, lower control over variation for multi-layer system compared to incumbent	Higher throughput, large area patterning capability
Inkjet Printing	Lower cost through novel application of mature technology, additive process	Lower speed and integration density	Higher throughput, rapid turnaround time, printing on flexible substrates
Soft Lithography	Lower cost due to elimination of optical lithography equipment	Higher integration density	Capability for feature definition on non-planar surfaces, variety of substrates and applications
Spherical Integrated Circuit Processing	Lower cost, cleanroom facilities not required due to processing in hermetically sealed tubes	Lower integration density as it is limited by size of single crystal silicon spheres, lower heat dissipation capabilities	Novel applications for sensors due to greater area for patterning for each tiny sphere

Table 6 Comparison of Disruptive Technologies

A comparison of the disruptive semiconductor manufacturing techniques which can be applied for RFID manufacturing in the future is illustrated in Table 6. It is critical to note that most of the emerging technologies are in early stages of development and will improve with more focused research and development efforts to compete with the incumbent technologies in traditional performance. This could have a significant impact on the industry structure with the emergence of technological leaders who have developed expertise in polymer chemistry, organic thin film transistors, and inkjet printing processes using conductive inks.

9.4 Innovations in Packaging and Assembly

Lastly, innovations in packaging and assembly are explored. These can be used in conjunction with current semiconductor manufacturing processes to reduce the cost of manufacturing of RFID tags. In addition they can be extended to work with next generation disruptive technologies as well. In case of inkjet printing where an additive process is used, the assembly process may be skipped due to monolithic construction of the die and the antenna on the substrate. Another observation is the possibility of extending the chip on paper assembly technique to fabricate smart odor sensors which also rely on change in electrical conductivity of conductive carbon ink to detect smell.

9.5 Future Work

A critical area of future research would be to perfect these techniques for fabrication of RFID tags which do not require feature sizes comparable to current generation optical lithographic process. This will enable progress in maturing the process which may be applied to address challenges in next generation lithography which do not have a low cost solution using optical techniques. This observation fits very well with patterns of disruptive technologies observed in numerous industries.

A viable technology strategy for firms entering RFID tag manufacturing segment could be to leverage older generations of IC fabrication processes since capital costs would have depreciated the cost of acquiring these production lines and leverage the innovations in assembly and packaging to enable low cost, high throughput manufacturing. At the same time, they need to invest in research and development in emerging areas of semiconductor manufacturing discussed in this research to develop a mature and cost effective process to manufacture complex RFID tags which may be required in the future.

9.6 Chapter Summary

The results of the research is summarized in this chapter. The salient points of the disruptive technologies are discussed along with a comparison of the key characteristics within the framework of Christensen's model for disruptive technologies. Recommendations to apply depreciated traditional semiconductor fabrication processes for current generation of RFID tag manufacturing with emphasis on investing in research and development to develop the disruptive technologies for RFID tag fabrication in the future are also detailed.

10 REFERENCES

[1] Andrew Kaplan, Tuning in to RFID, Food Logistics 5/15/2002

[2] Overby, Christine et al, RFID; The smart (R)evolution, Forrester Research August 2002

[3] Whiting, Rick, Data Avalanche, Information Week 2/16/2004

[4] Garry, Michael, Gearing up for the EPC, Supermarket News, 50(34) 19-8/26/2002

[5] Sarma, Sanjay, Towards the 5 c Tag, MIT Auto-ID WH-006, 2/1/2002

[6]Verma, A.K. et al., Fluidic self-assembly of silicon microstructures, Electronic Components and Technology Conference, 1995 Proceedings., 45th, 21-24 May 1995

[7]Scharfeld, T.A, An analysis of the fundamental constraints on low cost passive RFID system design, SM Thesis, Massachusetts Institute of Technology, August 2001

[8]Chou, Stephen et al, Nanoimprint Lithography, J.Vac Science Technology B 14(6), Nov-Dec 1996

[9]Xiaoyun Sun et al, Multilayer resist methods for nanoimprint lithography on non flat surfaces, Journal Vac. Science Technology B 16(6), Nov-Dec 1998

[10]Scheer, H,-C et. al., Problems of the nanoimprinting technique for nanometer scale pattern definition, Journal Vac.Science Technology B 16(6), Nov-Dec 1998

[11]Cheong et. al., Inkjet Printed Copper Source/Drain Metallization for Amorphous Silicon Thin Film Transistors, IEEE Electron Device Letters, Vol 21 No 8 August 2000

[12] Meridith Levinson, The RFID imperative, CIO Magazine, 12/1/2003

[13] Wykoff, Rich, Intel personal communication

[14]Want, Roy, RFID: A key to automating everything,, Scientific American: Jan 2004, Volume 290, Issue 1

[15]Kaplan, Andrew, Tuning in to RFID: will radio frequency identification technology revolutionize the food supply chain? , Food Logistics, 5/15/2002

[16]Stankevich, D.Garbato, Retail RFID initiatives move beyond Wal-Mart, Retail Merchandiser, 2/1/2004

[17]Wolfe, E, et. al, Tracking to the future: The impending RFID based inventory revolution, Bear Stearns Report June 2003, www.bearstearns.com

[18]Takaragi, Kazuo, An ultra small individual recognition security chip, IEEE Micro, Nov-Dec 2001

[19] Subirana, Brian, ESD 290 Spring 2004 lecture, Massachusetts Institute of Technology

[20]Crawley, Ed, System Architecture Fall 2003 lecture, Massachusetts Institute of Technology

[21]RFID finds its place, Electronic Business, 19(9):42, June 15, 2003. ISSN 1097-4881

[22] Krakow, Gary, Credit on your key ring, http://msnbc.msn.com/id/3072638/

[23] Utterback, James, Mastering the Dynamics of Innovation, Harvard School Press, 1996

[24] Fine, Charles, Clockspeed, Perseus Books, 1998

[25] Porter, Michael, Competitive Strategy, The Free Press 1998

[26] Ibid, page 22

[27] Chou, Stephen, http://www.ee.princeton.edu/~chouweb/newproject/page3.html

[28]Colburn, Matthew et. al., Step and Flash Imprint Lithography: An Alternative Approach to High-Resolution Patterning, Proc. of SPIE Symposium on Microlithography: Emerging Lithographic Technologies III, 1999

[29]Colburn, Matthew et al., Step and Flash Imprint Lithography for Sub-l00 nm Patterning, SPIE's 25th Intl. Symp. Microlithography: Emerging Lithographic Technologies IV, Santa Clara, CA, 2000

[30] Kawase, Takeo et al, Inkjet printing of polymer thin film transistors, Thin Solid Films, 438-439, 2003

[31]Min Hong, Cheong et al, Inkjet printed copper source/drain metallization for amorphous silicon thin-film transistors, IEEE Electron Device Letters, Vol. 21, No 8, August 2000

[32] Redinger, David et al, An all-printed passive component technology for low cost RFID, Device Research Conference, 2003, June2003, Page(s): 187 -188

[33] Whitesides, George et al, Soft Lithography, Angew. Chem. Int. Ed 1998, 37, 550-575

[34] Wilbur, J.L et al, Adv. Mater. 1994, 6, 600-604

[35] Xia, Y et al, Adv. Mater. 1996, 8, 1015-1017

[36] http://www.ballsemi.com/NEW/BallTech/Wspherical/Wspherical.asp

[37] Landesberger et al, New process scheme for wafer thinning and stress free separation of Ultra thin IC's, Proc. Of Microsystems Technologies 2001, Mesago Stuttgart, pp 43-45, 2001

[38]Yeh et al, Fluidic Self-Assembly of microstructures and its application to the integration of GaAs on Si, Sensors and Materials, vol 6, pp 319-332, 1992

[39]Rasul, S. Jad, Chip on paper technology utilizing anisotropically conductive adhesive for smart label applications, Microelectronics Reliability 44 (2004), pp 135-140

[40] Severin, Erik, Cyrano sciences' Sensor technology-The heart of the Cyranose® 320, http://cyranosciences.com/technology/sensor.html

[41]Arneson, Mike, PICA-Low Cost, High-Volume RFID Tag production, http://www.matrics.com/manufacturing/

[42] Weiser, Mark, The Computer for the 21st Century, Scientific American, vol 265, No 3

[43]Security technology: Where's the smart money?, The Economist, pages 69-70, 2/9/2002

[44] Garfinkel,S, A RFID Bill of Rights, Technology Review, October 2002

[45]Bak, David, Paper transponder cuts RFID costs, Global Design News 594):24 9/2001

[46]Weiss, S.A. et al., Security and privacy aspects of low cost RFID systems, First International Conference on Security in Pervasive Computing, 2003

[47]Sarma, E.Sanjay, RFID systems and security and privacy implications, www.autoidcenter.org

[48]Juels, Ari, Privacy and Authentication in Low Cost RFID tags, http://www.rsasecurity.com/rsalabs/staff/bios/ajuels/publications/pt-rfid/