Radio Frequency Identification (RFID) Applications in Semiconductor Manufacturing

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Abstract

Radio frequency identification (RFID) has an enormous potential impact within the semiconductor supply chain, especially within semiconductor manufacturing. The end benefit of RFID will be in the mass serialization, and the subsequent tracking and tracing, of individual semiconductors, or what is referred to as Unit Level Traceability (ULT). Before all of the technical hurdles of ULT are overcome, however, there exists a host of other applications for RFID within semiconductor manufacturing. The identification of what can and what should be RFID-tagged and read, the analysis of how to collect this information and what to do with the data, and the implementation of some targeted opportunities will provides valuable information with regards to the technical and logistical hurdles of RFID within semiconductor manufacturing far before ULT becomes a reality.

Thesis Supervisor: James B. Rice, Jr.
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Table of Contents

List of Tables

List of Figures

1 Introduction

1.1 Background and Motivation

The last several years have seen dramatic new developments in the evolution of *radio frequency identification* technology, better known as RFID. Although this technology for automated identification of objects has been in existence for several decades, advances in several enabling technologies—including Internet and microelectronics—have facilitated continuing improvement in features and cost. At the same time, the increasing pace of standardization efforts, led by organizations like MIT's Auto-ID Center/Auto-ID Labs, has helped smooth the way to widespread adoption.

Much of the initial effort in this current push for adoption focused on the ways that RFID could increase product visibility in the inter-company supply chain, particularly for consumer packaged goods between the supplier's distribution center and the retailer's shelves. That is, by allowing automatic, machine identification of objects, it enables the collection of more data that would not be collected if manual operations were relied upon; these added data allow for closer tracking at more points in the chain. Continuing efforts have sought to investigate pushing that visibility further back in the chain, and within the factory's four walls.

The semiconductor industry is among the most logistics-intensive industries due to its high capital costs and relatively long lead times, owing to the dual complexities of design and manufacturing. It seems reasonable that the newly emerging (and promising) supply-chain technology of RFID could be applied to effect improvement in the manufacturing processes for semiconductors.

With this in mind, a project was initiated to research some possible applications of RFID in semiconductor manufacturing. In order to gain a proper understanding of the issues surrounding this use of the technology, it was necessary to gain an understanding of the semiconductor manufacturing process, as well as the details of RFID technology. This understanding was gained through a review of available literature and also through academic settings and interaction with experts in the respective fields. Further insight into RFID was gained through implementation and testing of a portable RFID reader. Armed with this knowledge, and in cooperation with a major manufacturer of semiconductors, possible applications of the technology in semiconductor manufacturing were examined, and some were chosen for more in-depth study.

1.2 Research Question

The primary research question is as follows: *What are the opportunities and obstacles for the use of RFID in semiconductor manufacturing?*

To be certain, there are many opportunities. Many feel that the largest opportunity of RFID in the semiconductor industry is to achieve unit level traceability (ULT) for the semiconductors themselves. ULT in this context refers to the ability to both identify and track individual semiconductors by way of mass serialization, much like how automobiles are tracked today with vehicle identification numbers (VINs). ULT has the potential to improve visibility in the forward and backward supply chain, increase efficiencies, and perhaps even enhance the end-customer experience, all through the automated assigning and easy retrieval of a simple serial number.

RFID simplifies this assignment and retrieval process and has the potential to provide much more valuable information on the semiconductor itself. Specific examples are provided in section 4.3.

There are many first steps that must be taken, however, before ULT by way of RFID will be achieved. There are other easier-to-implement and quicker-ROI opportunities for RFID within semiconductor manufacturing, and there are many lessons yet to be learned from the fledgling technology. The purpose of this paper, therefore, is to examine some of those initial steps and provide direction for further research.

2 Literature Review

2.1 Semiconductor Manufacturing Process and Market Overview

In this section, the research and findings in understanding the process of semiconductor manufacturing are reviewed, as well as the market realities surrounding the semiconductor industry. This understanding is essential to recognizing the benefits that RFID can provide, and the pitfalls to its implementation. The investigation included reference to written information, included in this section, and site visits/interviews, included in section 3 below.

In the strictest sense, the word *semiconductor* refers to a solid, crystalline material that has electrical conductivity greater than insulators, but less than materials that are considered good conductors. Common examples are germanium and silicon. These materials are essential in the manufacture of transistors and other electronic devices.[1] This status as the building block of transistors also made semiconductors the logical choice as the platform to develop integrated circuits, also known as "chips," which are now the most common form of semiconductor device. Thus, through common usage, semiconductor has come to refer to integrated circuits, as well as the material used to make them.

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[1] Dictionary.com, "Dictionary.com/semiconductor," http://dictionary.reference.com/search?q=semiconductor.

2.1.1 Manufacturing processes

Semiconductor manufacturing is one of the most advanced and tightly controlled processes in the world.[2] The process typically involves hundreds of steps, each of which must be executed with the greatest consistency and precision. Because the structures being fabricated are so small (measured in micrometers [10^{-6} m] or nanometers [10^{-9} m]), the atmosphere surrounding the process and the technicians carrying it out must be kept ultra-clean and free of contaminants.

The stringent requirements of the fabrication facility (or *fab*), plus the complexity of the process equipment used to carry it out, mean that the capital outlay for constructing and equipping a fab run into the many hundreds of millions or even billions of dollars. For example, it is estimated that by 2007 the cost of building a fab will reach $6 billion.[3] The pressure is significant, therefore, to maximize efficiency of the fabrication process, to realize the greatest return on investment.

2.1.1.1 Fabrication

The fabrication process begins with the creation of an *ingot*, a large shaped piece of crystalline silicon, which is sliced into *wafers*. The wafers are thin circular disks of silicon that are polished ultra-smooth to form the foundation for the circuit-fabrication processes to follow. From here, three general processes are executed multiple times to produce the chip's circuitry: *deposition,* or the creation of a layer of new material on the wafer; *patterning,* or the impression of a circuit-element blueprint onto the material; and *etching,* or the removal of unneeded material from the

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[2] International SEMATECH, "Corporate Information: Semiconductor Manufacturing Process," http://www.sematech.org/corporate/news/mfgproc/mfgproc.htm; Intel Corporation, "How Chips Are Made," http://www.intel.com/education/makingchips/index.htm?iid=intelmuseum+home_bechips&; Micron Technology Inc., "Concept to Consumer," http://www.micron.com/concept/landing.html; Applied Materials Inc., "How Chips Are Made," http://www.appliedmaterials.com/investors/annual_report_1999/how_chips_are_made.html.

emerging integrated circuit. Additional processing steps may also take place at various points in the process.

In deposition, a chemical or physical process is used to either to deposit a layer of new material on the wafer, or grow a layer of oxide. A layer of *photoresist,* a special light-sensitive chemical, is then placed over this layer.

To create the pattern for the elements on the chips, a *reticle* (or *mask*) is first created. The reticle contains clear areas and opaque areas, representing the elements of the emerging circuit. Ultraviolet light is shined through the mask onto the wafer, causing a chemical change in the photoresist in the exposed areas. After a develop process, only the unexposed regions remain.

In the etch process, the wafer is exposed to chemicals or energetic plasma. The etching agent eats away at the surface of the wafer, removing material in areas that are not protected by the patterned photoresist. Once the etching is complete, the remaining photoresist is stripped away using chemicals and/or water.

In between groups of processing steps, the deposited material is often re-polished to create a flat surface for the addition of the next layer, a process called *chemical mechanical planarization*, or CMP. Another processing step known as *ion implantation* uses a particle beam of energized ions fired at the surface of the material. The ions embed themselves into the material, changing its properties, e.g., making it more or less conductive.

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[3] Michael Kanellos, "A Fab Construction Job," C|Net News.com, http://news.com.com/2100-1001-981060.html.

Typically, the first few deposit/pattern/etch cycles in the process form the electronic components (transistors, resistors, capacitors) in the integrated circuit. Any additional cycles are employed to form the metal interconnects, the wires that create the actual circuit.

2.1.1.2 Probe

Probe is the first major test of the component, and takes place following the fabrication steps. The probe is a large computer-controlled machine that is outfitted with a special card containing probe needles. These needles are specially configured for the particular chip model being fabricated, so that when a wafer is placed in the machine the needles come in contact with the bond pads on each individual chip, or *die*.

The probes send electrical signals through the circuitry of the chip, allowing the machine to measure certain properties. At its most basic level, the probe step identifies die that are not suitable for sale to the end customer. In addition to identifying unacceptable die, the remaining dies are classified on the basis of the tests that the probe performs. For example, for processors, the probe may test operating frequency and voltage, which are important performance parameters that determine processor speed and suitability for use in laptop computers. Finally, the tests provide important data for statistical quality control.

Once the probe has completed its tests, the information on the test results must be stored for use later in the process. In a typical contemporary fab workflow, the information is stored in a separate database called a “wafer map,” located on the manufacturer’s system of networked computers. This information must be accessed by different computers (potentially at geographically remote locations) as the chip is rated for speed and usage.

2.1.1.3 Assembly/Package

Following probe and creation of the wafer map, the wafers are sent to assembly. Each wafer is mounted on a special frame with photosensitive tape. Before final processing and assembly, each individual die must be separated from the wafer (a process known as *singulation*), so the wafer is sent to special diamond saws that cut between each die. The sawn wafer, still held together by tiny seams of silicon and the tape layer, is then sent to a sorting machine. Ultraviolet light is directed at the tape to reduce its tackiness. The sorting machine takes each chip from the wafer and sorts them on the basis of the information in the wafer map, downloaded from the manufacturer's servers.

The next step in the process is to package the bare die in a plastic or ceramic package to protect it from the elements. There are several types of packaging, depending on the specific needs of the chip and its application. The qualities the packages hold in common include mounting of the die to a substrate, which facilitates the connection of the chip with the outside world; a method of protecting the die; and a system for connecting the package to the printed circuit board in the final product. Depending on the type of chip, additional passive components (resistors, capacitors, etc.) may also be connected to the substrate.

2.1.1.4 Test

Once the packaging is complete, the component is subjected to another battery of tests. In particular, it is placed into a "testing oven," an apparatus which subjects the chip to various types of electrical tests while at the same time applying specific ranges of temperature. These temperature ranges simulate the potential conditions for the chip in use.

2.1.2 Market

2.1.2.1 Inventory value

Many types of chips, particularly processors, have a high intrinsic value compared to their weight and volume. This fact, coupled with a fairly accessible black market for such components, means that the chips are likely targets for theft. Particular steps must be taken in the supply chain respecting this fact; for example, the packaging of a shipment is generally very generic, revealing nothing about the contents. This high value also brings about high inventory holding costs, all else being equal, placing a premium on efficient operation of the supply chain.

2.1.2.2 Product pricing

For many integrated circuits, and particularly for processors and related chips, the design for the chip only partially defines its relevant performance. There are certain properties of the chip resulting from the particular conditions during production that also materially affect the performance of the chip, and can only be determined by testing after fabrication, as noted above. Therefore, performance-classification decisions are made late in the fabrication process, and this information must follow the chip as it is separated from the wafer, assembled, packaged, tested, and sold.

One unique aspect of this chain of events is that at the time a determination of performance has been made, a substantial fraction of the total cost of producing the final product has already been sunk. This makes improving yield of good die from each wafer profoundly important, and provides motivation to chip producers to seek out techniques that can improve manufacturing operations. It also means that any additional revenue that can be realized by improving the resolution of different performance parameters essentially becomes marginal profit. This yield management is the subject of concurrent research into the use of RFID in the semiconductor industry.[4]

2.1.2.3 Counterfeiting/diversion

In addition to outright theft, chips are also subject to less overt forms of misconduct. One possibility is a form of counterfeiting. Although it is unlikely that any but a legitimate organization would actually fabricate chips, they are subject to a type of counterfeiting that is analogous to "raising a note" in currency. In this case, the counterfeiter may alter the labeling on the package to make it appear that the chip is a more valuable model or performance level. In this way the "raised" chip could be sold for a higher price.

Another possibility is the diversion of legitimate goods. One form of this that was described by an employee of a major manufacturer of semiconductors involves packaged sets of components. For example, the chip may be packaged together with other components and sold as a unit for a certain price. The diverter will take individual chips and package them with cheap versions of the components, but sell the package at the same price. The manufacturer therefore loses revenue from the sale of the packaged components, and also may face warranty claims if the lower-quality components fail prematurely.

2.2 RFID Technology Overview

This section gives an overview of radio frequency identification technology: its operating principles, characteristics, capabilities, and limitations. This information was gleaned from

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[4] J.D. Kinley, "RFID ROI," unpublished Master's thesis, Massachusetts Institute of Technology, 2004.

industry technology overviews,[5] research papers from groups such as the Auto-ID Center/Auto-ID Labs, and coursework in MIT's innovative curriculum on the business impacts of RFID.

In general, RFID is a system that allows machine identification of physical objects. The current prevailing system for machine identification is the barcode; although barcodes have fulfilled their function well, they do possess certain limitations. Among these are the need for line-of-sight contact with the barcode, limitations in range, and limitations on the amount of data that can be stored in the code. RFID technology can address these limitations, allowing in particular for individual numbering of objects, rather than just object classes.

Although RFID addresses many of the barcode's shortcomings, it is subject to limitations of its own. For example, because RFID relies on radio-frequency communication, it is subject to interference by other radio sources. Depending on the operating frequency of the system, RF signals can also be blocked by certain materials, such as metals, water, or the human body. Improperly blocked signals can also be a problem; for example, one industrial-espionage scenario suggests that a spy armed with a reader could scan a competitor's inventory without ever entering their warehouse building.

2.2.1 RFID vs. Auto-ID

Radio frequency identification technology has been around since at least World War II, when it was used in the IFF (identification: friend or foe) systems in Allied aircraft. Development of the technology continued through the late 1990s, benefiting from advances in related fields, such as the invention of the transistor and the integrated circuit. However, the technology remained

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[5] AIM Inc., *Radio Frequency Identification RFID – A Basic Primer [AIM Inc. WP-98/002R2]* (Pittsburgh, PA: AIM,
(Footnotes continued on next page…)

relegated to niche markets, due to a lack of standardization and companies' concentration on adding features rather than cutting costs, particularly the cost of tags.

The Auto-ID Center was founded at MIT in 1999 with two principal goals: establish industry standards to manage the technology, and work to reduce the costs of RFID components. Although the initial thrust of the Center's research was focused on consumer packaged goods, later efforts also included manufacturing and other areas. The Center included several academic institutions, sponsored by a broad representation from industry and commerce. The ultimate aim of the Center's research was to create an "internet of things," a system of identifying individual physical objects, anytime and anywhere.

Through the Auto-ID Center's efforts, several standard technologies were created, including the electronic product code or ePC, an extension of the concept of the universal product code (UPC) that allows individual items to be identified, rather than just classes. Other standards govern the tag design; the method of locating computers with information on a particular product, known as the Object Name Service or ONS; an XML-based markup language used to create product information, known as the Physical Markup Language or PML; and an overall network architecture including readers, back-office servers, and a smart filtering system called Savant.

Having achieved its goals and created the initial set of standards necessary to implement the vision of ubiquitous RFID, the Auto-ID Center was retired in 2003. The standards and technology, along with the mandate to implement them in industry and carry them forward, were handed over to EPCGlobal, an industry consortium of U.S. and European companies. The

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Inc.).

research agenda continues to be prosecuted by Auto-ID Labs, comprising the academic institutions that participated in the original Auto-ID Center.

It is important to understand, then, that RFID and Auto-ID are not synonymous. Auto-ID represents the technology platform originally promulgated by the Auto-ID Center, characterized by inexpensive, limited-ability tags, intelligence of the system contained on networked computing resources, and a federated, Internet-based architecture. RFID encompasses this platform, plus any other application of the technology, such as proprietary systems, other international standards, etc.

2.2.2 Components

2.2.2.1 Transponders (tags)

Transponders, or more commonly, tags, are small, self-contained radio-frequency devices designed to respond to the appropriate transmitted signal by transmitting the data it contains. Because there is no physical connection between the tag and the device reading it, the two are said to be communicating across the air interface.

The basic components of a tag are memory, digital control logic circuitry, analog circuitry for radio communication and power handling, the power source, and the antenna. The function of these individual parts will be expanded upon in the sections below. The physical form of the tag varies with application; industrial or logistical applications require more protective housings, for example, than retail applications. Tags can be encased in plastic, incorporated into adhesive or cloth labels, shaped like screws for embedment into wood objects, or even inserted into an animal's body.

2.2.2.2 Readers

The reader, sometimes called an interrogator, sends the signal to the tag requesting its data and receives back the response from the tag, which it decodes and forwards to the computer/network to which it is connected. Because the signal received back from the tag is often quite weak, the reader must perform amplification, signal conditioning, and error checking and correction. The reader must also implement protocols to deal with concurrent responses from multiple tags (collision management), such as commanding certain tags to stop responding to sort out individual tags.

2.2.2.3 Information infrastructure

Since the goal of RFID is machine identification of objects, the reader must be connected to some type of information infrastructure that can take the data read from the tag, associate it with an object, and make productive use of it. The nature of the infrastructure depends on the specific need that RFID technology is filling, but typically involves networked communications, one or more centralized databases, and hardware and software to control the flow and storage of data.

One important function of the information infrastructure is to intelligently filter the raw tag reads streaming in from the environment. For example, in a retail-shelf application, the reader may take reads of all tags within range once every few seconds. This would result in hundreds of reads of the same tag every hour, but the application only requires recognition of two events: when the item arrived, and when it was removed. There is no need to store every read of the same tag in a database, only these two events, so a filtering program may be put in place that takes the raw data of the tag reads and returns to the database only the "enter" and "leave" events. This filtering is one of the functions of the Savant in the Auto-ID architecture.

2.2.3 Tag characteristics

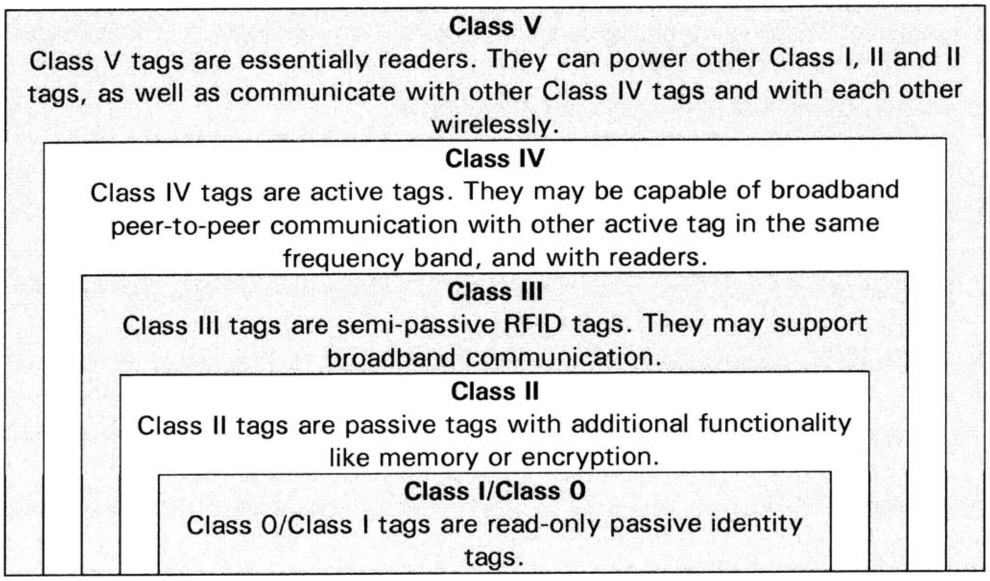
In designing an RFID system, several choices related to the physics of the system that affect the system's performance must be made. Because the tags will be the most ubiquitous of the elements of an RFID system, the system is generally thought of in terms of the tags. Working from this viewpoint, the following discussion centers on how these characteristics affect the tag capabilities, though of course they have implications for other components of the system as well.

2.2.3.1 Active/passive

One fundamental choice to make regarding tag design is whether the tag includes its own power source, most commonly in the form of batteries. It is also possible to create a tag which can take its power from the signal broadcast by the reader, and therefore requires no on-board power source. In industry parlance, tags with on-board power are known as active tags, while those without are known as passive tags. There is also a third type, semi-passive, which uses a power source to power the digital logic on the chip, but not to communicate with the reader.

The choice of active versus passive has certain ramifications for the life cycle of the tag. Principal among these is the fact that there is a finite lifetime for the tag (though, for many high-performance systems, that lifetime can be as much as ten years). Batteries can be replaced, but doing so requires detection of tags with dead or dying batteries or implementation of a maintenance schedule to select tags for battery replacement. One important trade-off for accepting the constraints of an active-tag system is that an active tag typically has much greater range. Thus, although an active tag may be considered less reliable because its power source may fail, communication with the tag is often much more reliable because of this improved performance. Another important factor in the active/passive decision is the price of individual tags; active tags are typically more expensive than passive tags.

The Auto-ID Center created a useful framework for classifying the different tag types, which is reproduced below.[6]



Class V

Class V tags are essentially readers. They can power other Class I, II and II tags, as well as communicate with other Class IV tags and with each other wirelessly.

Class IV

Class IV tags are active tags. They may be capable of broadband peer-to-peer communication with other active tag in the same frequency band, and with readers.

Class III

Class III tags are semi-passive RFID tags. They may support broadband communication.

Class II

Class II tags are passive tags with additional functionality like memory or encryption.

Class I/Class 0

Class 0/Class I tags are read-only passive identity tags.

Table 1 Auto-ID Tag Class Structure

2.2.3.2 Operating frequency

As with most radio-frequency applications, a typical tag operates at a specific carrier frequency. This frequency is pervasive throughout a particular system, that is, all tags and all readers will use the same frequency to maximize utility of the system. The choice of carrier frequency affects several properties of the system, and is affected by certain operational realities.

One of the chief sources of complication in RFID system design for use in logistics and manufacturing is the varied regulatory landscape. Each country has a government body (the

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[6] Sanjay Sarma and Daniel W. Engels, *On the Future of RFID Tags and Protocols [MIT-AUTOID-TR-018]* (Cambridge, MA: MIT Auto-ID Center), 6.

Federal Communications Commission in the U.S., for example) that regulates the radio-frequency spectrum. Typically, usage of the spectrum is regulated on the basis of bands of frequencies, reserved for a particular set of purposes. RFID systems seek to operate in ranges that do not require licensure, since this would add cost and administrative overhead that would hamper adoption. However, such frequency bands have been parceled out differently by different countries' regulators. There is some regional uniformity, but the absence of consistent suitable frequencies worldwide makes system design a challenge.

In order for wireless communication to take place, the transmitter and receiver must be *coupled,* or connected across the air interface. There are several modes of coupling, but the two most common modes in RFID applications are *inductive* and *far-field.* Inductive, or magnetic, coupling is coupling of electromagnetic fields, in an operating principle similar to that of electrical transformers. Inductive coupling requires that the transmitter and receiver be relatively close together. Far-field propagation, or electromagnetic, coupling is the mode in action for most types of wireless communication, e.g., wireless phones, broadcast radio. Far-field propagation, as the name suggests, allows for longer-range transmission than inductive coupling.

Different frequency ranges are associated with different coupling modes. For example, 13.56 MHz, a frequency in the so-called high-frequency (HF) band used in RFID proximity-card applications, is associated with inductive coupling. 915 MHz, in the ultra-high-frequency (UHF) band, and 2.4 GHz, in the microwave (MW) band, are associated with far-field propagation. Because frequencies operate with different coupling modes, and coupling modes are linked to certain ranges of operation, this pairing of properties is one factor that affects range of RFID systems.

Other factors can affect range, as well. Range exhibits a generally increasing trend with increasing frequency through HF and UHF bands, but dips downward again in the microwave region. The reason for this is that MW waves are affected by water, which is present in the atmosphere in tiny amounts virtually everywhere on earth.

Operating frequency is also closely linked to speed of data transmission. All else being equal, higher frequencies enable higher-speed data transmission. In practice, other factors, such as environmental noise, interference and obstructions also affect transmission speed.

In summary, the operating frequency of the RFID system must be chosen to harmonize with regulatory requirements in the jurisdiction in which it is installed. Frequency is closely tied to range, with increasing frequency generally affording increasing range up to the UHF range, and then some decrease in range into the microwave range. Higher frequency also allows for faster data transmission between tag and reader.

2.2.3.3 Data storage

As noted above, an integral part of the makeup of a tag is digital memory. Some amount of memory will be included in the tag that contains its operating instructions, its "operating system," as it were. Some random-access memory (RAM) will also typically be included to provide the tag with workspace to store intermediate values as it processes commands and data.

Finally, and perhaps of greatest importance, the tag must include some form of non-volatile memory, that is, memory that retains stored values after power to the memory ceases. This is used to store whatever useful information the tag is meant to carry. Typically, active tags have greater data storage than passive tags.

2.2.3.4 Programmability

Connected with the memory capacity of the tag is its level of programmability. At the simplest level (Class 0/Class I in the Auto-ID framework) are the so-called write-once, read-many (WORM) tags, which are written with data one time, typically at manufacturing, and from that point on can only be read. The data written to such tags is usually a unique identifier number. Some tags at higher levels of sophistication have a portion of memory that can be written to only once (and again usually containing a unique ID), and another portion of memory that can be written to and read from many times. Increasing sophistication, usually reserved for semi-passive or active tags, may include security features like encryption, or communication features like interaction with other tags.

2.2.3.5 Cost

As with most things, the trade-off for more features and/or greater reliability is cost. Factors that can result in a higher cost per tag include higher frequency, more memory, greater programmability, and active rather than passive operation. Per-tag cost is an important consideration, as this cost is variable and ongoing while the system is still in use and new items are tagged. One of the fundamental assertions of the Auto-ID Center was that tag prices would have to dip below five cents each in order for universal tagging to take place; it was this requirement that drove the Center toward their proposed ePC architecture, which included tags with only a unique ID number.

2.2.4 Applications in manufacturing

Many applications in manufacturing relate to the view of the manufacturing floor as a "micro supply chain," with early steps in the manufacturing process acting as suppliers to later steps. In this context, use of RFID takes advantage of the improved visibility it imparts, along with the ability for automated tools to identify objects. The following are representative concepts for application of RFID in manufacturing that exploit these ideas.

One scenario for use of RFID in manufacturing involves the preparation of custom gift boxes.[7] The empty box is tagged and placed in a loading station. A robot-driven loading system then reads the tag to retrieve the order listing, and automatically fills the box based on the listing. This application could be extrapolated to kitting operations for processes that involve parallel assembly workstations, or even to robotics-driven assembly.

In a similar variant of this scenario, a reusable pallet is tagged, either with a unique ID number or with a more complex tag with greater memory capacity. Information is then stored, either on a networked database or on the tag itself, for a custom order of a manufactured item (for example, color and size information for a custom bicycle). Automatic or human-operated readers at each station then read the tag and perform the appropriate steps based on the order specifications. Once the item is complete, it is removed and shipped, and the pallet is sent back to the head of the line. For some larger items, such as automobiles, the tag can be placed directly on the work, assuming that an application point can be found that is both unobtrusive and not an obstruction to the RFID signal.[8]

Another piece of the manufacturing process that can be improved, particularly when units are individually tagged, is quality control. When units are individually identifiable, tracking and control are possible at a more granular level; if a series of parts requires re-work, it is also easier

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[7] Duncan McFarlane and Yossi Sheffi, "The Impact of Automatic Identification on Supply Chain Operations," *The International Journal of Logistics Management* 14, no. 1 (2003): 13-14.

to locate them. Extending this notion outside the plant, RFID may also ease the recall process by making recalled units easier to locate and identify, and by narrowing the set size for the recalled units.

RFID technology already has been implemented in parts of the semiconductor manufacturing process, largely in the area of materials handling systems. Particularly with the advent of the newest wafer-size standard (300-mm diameter), automated material handling has become the preferred method for moving materials from one process to another. An RFID tag is incorporated into the wafer-handling boxes, known in industry parlance as front-opening unified pods (FOUPs), and readers are incorporated into fabrication tools. It is then possible for the material to be tracked, and matched to the correct "recipe" of options for each wafer.

Although there may be unique new applications for RFID in manufacturing that have yet to be conceived, the applications described above, which build on current notions of automation and tracking work through process, are examples of straightforward and relatively easy-to-implement applications. These "low-hanging fruit" will allow the concept of RFID in the manufacturing plant to be proven, opening the doors for future touchstone applications of the technology.

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[8] Alexander Brewer, Nancy Sloan, and Thomas L. Landers, "Intelligent Tracking in Manufacturing," *Journal of Intelligent Manufacturing* 10, 245-50.

3 Methodology

The methodology undertaken in this study was to explore the worlds of semiconductor manufacturing and RFID, and to determine where the intersections might occur. Once these intersections were discovered, the goal was to evaluate and rate the opportunities, and then choose at least two opportunities to explore at greater depth and report on our findings.

3.1 Understanding RFID and the Supply Chain

Even though RFID is not a particularly new technology, much of the literature and excitement about the technology has been generated during the past four years. Therefore, most of the available information is recent and being constantly updated with new information. It became the task of the researchers to quickly and thoroughly understand the ins and outs of RFID and to keep abreast of the changes in the technology, its adoption, and the business landscape.

3.1.1 CPG warehouse (w/ RFID field trial) visit

One of the first visits to an RFID-equipped facility was to a consumer packaged goods (CPG) `warehouse in northeastern Massachusetts, belonging to a major producer of personal-hygiene and other products. Portions of the warehouse served as a live working laboratory for potential RFID applications, the pilot studies concerning the receiving, inventorying, and tracking of razor blades. The two primary applications under test at the time of our visit were a portal through which pallets of RFID-tagged cases had to pass upon receipt or shipment, and a row of inventory shelves for the static reading of cases of the company's line of razor blades for women.

The field trials at this manufacturer concluded that RFID-tagged pallets and cases were much more easily read when the case or pallet was in motion. In fact, they equipped their portals such that as items were moved into or out of the portal, the entire pallet rotated 720 degrees to ensure reads.

Also, the company developed a method they referred to as "aggregation" by which, once a pallet was formed out of its associated cases, only one case on the pallet had to be read in order to register a positive read for the entire pallet.

3.1.2 Meetings with RFID experts and Auto-ID Labs personnel

Meetings with RFID experts included visits to the Auto-ID Labs in Cambridge, MA. Initial visits were aimed at understanding the world of RFID applications by segmenting the marketplace and identifying opportunities within each realm. Subsequent visits included more specific business case discussions, as well as tours of the retail simulation labs themselves.

3.1.3 Meetings with Supply-Chain Experts

The researchers had unique access to some of the top minds in the world of supply chain management, including Professor Hau Lee from Stanford University, and Professor Yossi Sheffi and Jim Rice from the Massachusetts Institute of Technology. For example, the researchers had the opportunity to witness Hau Lee actually create frameworks with which to characterize the world of RFID and its relation to supply chain management. A case in point is the following framework Hau Lee presented at the 2004 Zaragoza International Logistics Summit in order to describe how he envisioned the evolution of RFID's effect on the world of supply chain management, starting with simple substitution, progressing to a scale effect, and finally evolving into a structural effect that has the potential to truly transform supply chains and how one thinks of them.

RFID Evolution[9]

	Opportunity	Values
Substitution Effect	Inventory audit, product information	Fast checkouts/payments, inventory control, theft prevention, reduced spoilage
Scale Effect	Tracking, visibility, monitoring	Inventory location & control, asset management, product recall, product origin tracking
Structural Effect	Intelligent supply chain services	Security, virtual supply chain, mfg process redesign, smart product/service/store

Table 2 Evolution of RFID Applications

Initially, RFID will be used simply to supplant barcodes and magnetic strips with little change to the way business is currently conducted, save for time and process efficiencies with the potential to nominally reduce headcount. This is referred to as the substitution effect. The scale effect refers to the phenomenon of RFID used on a much wider scale, not just substituting current barcode applications, but finding uses in a broader array of potential applications, or to a greater extent and with much higher efficiencies than is done today. For example, inventories will be taken in real time, product recalls will be more targeted, and asset management will become far

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[9] Hau Lee, "Information Based Supply-Chain Innovations," *Zaragoza International Logistics Summit*, 24-26 March, 2004.

easier to implement. The structural effect, on the other hand, refers to a complete and total paradigm shift as to what one thinks of a supply chain because of the effects of RFID.

RFID, for example, will enable manufacturing processes to become highly specialized, especially with regards to product or package recipes. It will lead to a complete redesign of both the warehouse and the store of the future. It will also allow for more intelligent objects that are "aware" of their location and history, which by itself can lead to greater security, more detailed and reliable product pedigree, and other new and unforeseen applications for information.

3.1.4 RFID Coursework

A fruitful part of the RFID exploration came about with the opportunity to enroll in a first-of-its-kind class offered by the Massachusetts Institute of Technology's Engineering Systems Division. The class, entitled "Business Impact of RFID and Auto-ID," and taught in part by Auto-ID Center founder Sanjay Sarma, was aimed at presenting all aspects of RFID to the student, including physics, ethics and legal issues, and economics. A description of the class follows:

> This course is centered on how RFID systems will transform the business landscape, with a particular emphasis on the supply chain. The course will take an interdisciplinary approach to analyzing the various aspects of a modern RFID system. Lectures will review technical components of RFID systems, supply chain management process analysis, value and productivity performance measurement of IT investments, legal, policy and regulatory aspects of auto-identification and the impact of RFID on business strategy. By the end of this course students will have a detailed understanding of the important components of an RFID system, and how it interacts with most aspects of a business, from logistics to finance, strategy and IT.

An optional extension to this course involved what the professors referred to as the "Staples Challenge." It involved designing, developing, and evaluating specific RFID applications in the consumer retail space for presentation to Staples Inc. corporate executives. One researcher's team thoroughly analyzed an RFID Business Customer Card, which would assist in the quick identification of high-value customers and which could be coupled with an RFID-equipped "smart" shopping to assist the customer in their shopping experience.

Taken together, the experiences offered in the class above broadened the view of both researchers into RFID applications outside of the semiconductor manufacturing environment, and provided valuable information with regards to the more general technical and business aspects of RFID.

3.2 Understanding the Semiconductor Industry

Although both researchers were familiar with the semiconductor industry in general and its supply chain in particular, a study was undertaken to become thoroughly familiar with a subset of semiconductor manufacturing: the assembly and test facility. This study included multiple general and targeted tours of various semiconductor facilities, as well as access to some of the leading researchers working with RFID in semiconductor manufacturing.

3.2.1 Semiconductor Assembly/Test Plant visit

The researchers had the opportunity to visit a large and modern test and assembly facility on multiple occasions. During this time, they became very familiar with the processes described in 2.1.1.3, and 2.1.1.4. They also had the opportunity to both learn about and identify for themselves opportunities for RFID applications with regards to product tracking and manufacturing process redesign.

3.2.2 Semiconductor Warehouse visit

The semiconductor warehouse associated with the above-mentioned manufacturing facility provided yet more insight and brought to mind more applications and implications for RFID's use in the semiconductor industry.

The most obvious application was the tracking of product from the factory floor through the warehouse and onto the shipping dock for customer delivery. This tracking, as will be shown later, could be accomplished at multiple levels of aggregation. A first step, as will be highlighted in section 3.4.2, is the tracking of boxes of finished product from the factory into the warehouse. The tracking of the carts that act as vehicles for these boxes represented an additional opportunity for RFID in the warehouse.

Although the warehouse was adjacent to the shipping dock and thus associated with outgoing finished product, it also served as a receiving dock for returned items. This sparked discussion as to the end benefits of Unit Level Traceability for returned materials. ULT could benefit the RMA process in two ways: First, it could dramatically reduce warehouse labor by simplifying the step by which employees must open every incoming package and verify that the contents match the waybill. Second, it could provide much faster and much more accurate traceability of returns, and thus provide a means of root cause analysis for failures in the field.

3.2.3 Meetings with Industry Experts

In addition to the multiple opportunities to conduct fieldwork at semiconductor facilities, the researchers had access to veterans of the semiconductor industry who were able to either answer any questions the researchers had, or to direct them to the correct authority. The experts had themselves conducted field trials of targeted RFID applications in the semiconductor assembly space, and had both lessons to relate and ideas for further applications.

3.3 Devise Frameworks to Analyze Applications

Based on the above learnings and new understandings of both the world of RFID and that of the semiconductor assembly and test operations, frameworks were devised under which to analyze the intersection of these two worlds. First, a comprehensive list was generated of all the possible "things" within a semiconductor assembly and test facility that could be tagged. Additionally, a task was undertaken to understand the different ways in which RFID readers could operate and effect change in both this and other industries.

The tagging framework was devised after looking at the entire world of things that could be tagged within semiconductor assembly and test. It was very important that all objects were analyzed at each level of aggregation. That is, it was important to understand that objects could be tagged at various hierarchical levels, all the way down to the unit level, and that tradeoffs occurred at each level of aggregation. After identifying as many applications as possible, each case was evaluated at face value based on its own benefits, difficulties, and implications.

The reading framework was devised after realizing that RFID could do much more than simply supplant the current barcoding paradigm. In fact, the current world of barcoding was simply one paradigm in which RFID could exist. By analyzing the different ways readers could be used, and the different ways in which items could be read, a 2 × 2 matrix was devised through which to look at this world of reading.

3.4 *Applications for Further Investigation*

Once applications were identified, they could be analyzed through the dual lenses of both a tagging framework and a reading framework. The next step involved choosing a subset of these applications in order to conduct "deep dives", that is, to implement or further analyze actual applications to test the validity of the framework. The applications below represent a first stab at applications within semiconductor manufacturing.

3.4.1 iGlove

As a possible vehicle for RFID application in the semiconductor manufacturing environment, a small form-factor, portable RFID reader was proposed. A reader of this type had been designed and a specification published by Intel Research–Seattle, which generally fit these characteristics.[10]

The reader design in question incorporates several unique features. The core of the design is a 13.56 MHz RFID reader board, manufactured by SkyeTek, Inc. For power-efficient wireless communication from the reader to a base-station computer, the design incorporates "Mote" technology from Crossbow Technology, Inc. The design also includes an antenna to be connected to the reader board, a lithium rechargeable battery, and additional electronics to regulate power and allow communication between different parts of the reader.

Mote technology is a system of self-organizing sensors and wireless communication devices. The devices run a special low-footprint embedded operating system called TinyOS, developed at the University of California–Berkeley, that is specially designed for this application and optimized for low power consumption and limited computing resources. The system allows the individual agents to organize dynamically into a network to communicate results back to a central host, potentially reconfiguring as nodes drop out or optimal communication paths change. In the design for the reader, motes were used for their wireless-networking capabilities, with one mote connected to the reader and one connected to the base station computer. Special TinyOS applications are loaded onto the motes to give them their respective functionality as reader-controller or base-station.

For this implementation of the reader, it was decided to build the reader into a glove form, which could be theoretically worn by an operator while on the job. A fingerless glove (actually intended for wear by bicycle riders) was used as the foundation. The electronic components were mounted to the back of the hand, and the antenna wire was embedded into the palm of the glove. Photographs of the parts of the glove and the completed reader can be found in Appendix A. Thus configured, the reader was dubbed the iGlove.

As constructed, the reader polls about once per second, that is, it attempts to read tags within its range every second. At this read rate, and with the chosen battery, the reader reportedly continues to operate for approximately four hours. In the interest of improving this operating time, a few measures were considered. The easiest approach is to increase the capacity of the battery, although in general this comes at the cost of added weight; in this case, alternative locations might be considered for the battery, such as a belt pack or a pack on the wrist/lower arm. Another approach is the incorporation of some kind of switch, activated manually or when

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[10] Adam Rea, Pauline Powledge, and Gaetano Borriello, *Building and Using a Handheld RFID Reader* (Seattle, WA: Intel Research, 2003). Available at http://seattleweb.intel-research.net/projects/HandheldRFIDReader/.

the user grabs hold of a tagged object. Neither of these measures has been implemented in the current version, but they are possible improvement paths for future versions of the iGlove.

It is important to note that, as a 13.56 MHz reader, the iGlove works at generally short ranges. The range is partially dependent on the antenna design, but there is a practical limit to the reader's range in any case. During experimentation with the reader, other limitations were also found. For example, the antenna, which is configured as a loop with two turns in the palm of the glove, performs much better when the loop is plane; therefore, when the user's palm is bent, read performance declines.

3.4.2 "Shopping Cart" analogy

Another targeted application was that of the "Smart Cart." The idea of the smart cart was first devised for use in the grocery retail business. Basically, it is a shopping cart with the ability to read its own contents and thus provide added-value information to the consumer pushing the cart. For example, the cart could provide a running subtotal of the value of its contents, or it could provide information about the health content of the products or alternatives to those that are in the cart.

In the semiconductor industry, the analogy is for the mobile cages, or trolleys, used to transport finished product between the testing facility and the warehouse, to be able to keep track of its own contents. There is also the potential to track these trolleys simultaneously in real time, to provide 100% location tracking of the contents. This application was chosen as a potential application for RFID for a few reasons. 1) The value of the contents was particularly high, and 2) The concept of a mobile shelf represented the greatest paradigm shift away from the simple replacement of barcodes.

Further, tagging the contents of the cart (i.e., the semiconductor boxes) is analogous to the consumer packaged goods idea of case level tracking, and is an idea already being analyzed by major semiconductor manufacturers and PC suppliers.[11] A thorough analysis of this chosen application is provided in section 4.2.2.

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[11] Dennis Duckworth, "Potential for Utilization of Radio Frequency Identification in the Semiconductor Manufacturing Intermediate Supply Chain," unpublished Master's thesis, Massachusetts Institute of Technology, 2004.

4 Data and Results

4.1 Framework for Understanding

The above-described methodology yielded two important insights: 1) it is not always obvious *what* is the best information to collect (i.e., what "things" one might want to tag), and 2) it is equally ambiguous *how* to collect this information (i.e., *how* to read the tags).

The first insight came about with the realization that there were so many things within a semiconductor assembly plant that *could* be tracked and traced. Many of these things were already tracked with a high degree of efficiency and expense. Others were not tracked at all. To add to this complication, the things that could be tracked could be tracked at different levels of aggregation. This is analogous to the consumer packaged goods (CPG) industry, where things can be tracked (and tagged) at the pallet, case, and item level. Each level of aggregation brings with it a different set of costs and benefits.

The second insight was derived from the observation that the features of RFID offered new and completely different paradigms with regards to how an object might be identified. To be certain, RFID could be used to simply replace barcodes, or it could be used in new and imaginative ways, as discussed further below.

4.1.1 Tagging paradigms

One easily understood taxonomy in which to classify all of the items within a semiconductor assembly plant that might be tracked and traced with the benefit of RFID (with a few exceptions) is to divide all taggable items into three categories: 1) incoming product, 2) work-in-progress (WIP), and 3) outgoing product.

		Level of Aggregation			
		Low →			**High**
Incoming Product	Wafers	Unit	FOSB/FOUP		
	Passives	Unit	Reel		
	Substrates	Unit	Tray	Cart	
WIP	Dies	Unit	Reel	Lot	
	Die on Substrate	Unit	Tray	Cart	Lot
Outgoing Product	Semiconductors	Unit	Tray	Box	Trolley

Table 3 Tagging Candidates and Levels

Incoming product refers to product supplied by vendors (whether it be internal or external suppliers) into the four walls of the assembly plant via the receiving dock. WIP refers to just that: product that is in an unfinished or intermediate stage of assembly or other processing. Outgoing product refers to finished, packaged product on its way from the assembly plant to the warehouse or out the doors of the shipping dock to the final customer.

The tagging of both incoming and outgoing product potentially benefits the respective parts of the supply chain that they touch. Similarly, WIP tagging affects the manufacturing process within the four walls of the factory. In addition, however, the tagging and tracking of incoming and outgoing product has implications all the way into and all the way out of the manufacturing floor, as will become obvious in the examples below.

4.1.1.1 Incoming product

There are two general classes of incoming goods into a semiconductor assembly plant: processing materials and parts. Processing materials include chemicals used in the processing of semiconductors from whole wafers into individualized packaged dies in substrates. This might include solvents, de-ionized water, etc. These commodity items, because they are purchased in bulk and are relatively slow moving stocks, are not initial primary candidates for RFID tagging.

The other class of incoming products—that of parts required for the assembly of packaged semiconductors—includes wafers, substrates, passive components, and caps. All of these incoming products, because of their different packaging and form factors, and extremely disparate values, have different implications with regards to the eventual tracking and tracing in the supply chain.

4.1.1.1.1 Wafers

Wafers are by far the most valuable incoming product in a semiconductor assembly facility and are thus the most obvious candidate for RFID-tagging. However, the very nature and form of wafers makes their tagging a natural problem, one that will be encountered throughout the discussion: "At what level of aggregation should something be tracked, and likewise, tagged?"

Wafers are currently tracked primarily at two levels: the aggregate level and the item level. The aggregate level is through a plastic case called a front opening unified pod, (FOUP), or front opening shipping box (FOSB). Both types of case hold on average up to 25 wafers in a secure, air-tight environment during transport through the fab or between the fab and the assembly plant. The item level is the wafer itself.

4.1.1.1.1.1 FOSB/FOUP

FOSBs/FOUPs, with respect to wafers, are analogous to the case level within the CPG industry. FOUPs can be tracked using RFID or barcodes, and FOSBs are typically tracked with barcodes. Data associated with each FOSB/FOUP indicate the gross characteristics of the wafers therein, e.g., the wafer serial number. The only differentiation between the wafers is the order in which they are placed into the containers.

4.1.1.1.1.2 Wafers at unit level

Because each wafer is unique, it is very important that they are differentiated from each other. At the wafer unit level, RFID could serve to increase visibility of the wafers in both the supply chain and the manufacturing process.

Although it is outside of the scope of this thesis, it is noteworthy to mention that RFID could provide an increased level of visibility for wafer manufacturing in the fab itself, since the very fabrication of a wafer from bare silicon to finished product is itself a multi-week process, even before the wafer is delivered to the assembly facility.

Once it is inside the assembly plant, the wafer is stored within the FOUP or FOSB before it is ready for additional processing prior to singulation. A potential application of RFID is to "see" what is in each FOUP or FOSB without actually opening it up and looking inside.

4.1.1.1.2 Passive-component reels

Individual capacitors and other passive components make unsuitable candidates for RFID tags because of their extremely low value. Each passive component costs less than even the 5-cent goal the Auto-ID Center has set for the RFID tag itself. *Reels* of these passive components, on the other hand, make likely candidates for RFID tags for at least two different reasons, one with regards to the supply chain and one with regards to the manufacturing process.

First, because each reel holds thousands of passive components, they each have a value in the hundreds of dollars. Increased visibility and more secure receipt of these high value reels by itself might be enough of an argument to tag these items. The second reason, however, is even more compelling.

In the manufacturing and assembly process, the close tracking and tracing of these reels is essential so as to not mix them up with each other. Although rare, mistakes can cause excursions in the manufacturing process at a cost of millions if not tens of millions of dollars in irrecoverable inventory. A full analysis of this challenge and some of the proposed solutions using RFID are discussed in section 4.2.1 below.

4.1.1.1.3 Substrates

Substrates, that is, the part of the semiconductor that enables the connections on the die to interface with the exterior pad connections and communicate with the outside world, represent yet another major vendor-supplied incoming product on the manufacturing floor. Individual substrates are currently not barcoded. The tagging of substrates in some form is yet another opportunity for RFID, but for reasons very different from the ones argued above for either wafers or capacitor reels as explained below.

The primary difference between substrates and the other major incoming products is the relatively low value of each substrate. Although their value has been rising in recent years as more and more technology becomes integrated into the substrate, the cost for an individual substrate is usually in the cents or tens of cents. This means that a tray of substrates would rarely exceed a dollar in value, and even a cart of substrate trays would be valued at less than $10. Hardly a viable candidate for RFID in this respect, but as discussed below, substrates are a viable candidate for tagging at different levels for different reasons.

4.1.1.1.3.1 Substrate tray carts

Carts packed with incoming trays of substrates might at first appear the likely initial level of aggregation for the tagging and tracking of substrates, for at least two reasons. First, they are a high enough level of aggregation such that the number of substrates actually represents a dollar value worth tagging. Second, they represent a fairly large staging area for incoming substrates. However, because these carts of substrates are uniform with respect to each other (as opposed to wafers or dies), there is no virtually no point in differentiating them from one another. At this point in the manufacturing process, the substrates are plain vanilla with little value to track at this high level of aggregation.

4.1.1.1.3.2 Substrate trays

Substrate trays are the next lower level of aggregation below substrate tray carts, and are in fact the level of aggregation at which substrates are delivered to the factory. Trays, which hold as few as 8 but can hold over one hundred substrates, depending on the size of the finished product, are delivered by the substrate manufacturer in boxes, where a technician unloads the individual trays and loads them into the substrate carts described above.

Again, since the substrates are of low value and uniform with respect to one another, there is no need to differentiate between them. However, although these substrate trays carry low-value non-differentiable products at the front end of the manufacturing process, these same trays have the potential to carry much higher value WIP during the manufacturing process or finished product at the back end of the manufacturing process. With this in mind, substrate trays may provide a very practical case study for RFID in semiconductor manufacturing.

4.1.1.1.3.3 Substrates at unit level

Substrates at the unit level are hardly worth tagging because of their extremely low value and unlikelihood of mixing. But, as will be discussed below, tags on substrates might be a tactic to achieve unit level traceability for packaged semiconductors. That is, it might be beneficial to tag the substrates in order to track the high-value dies with which they are assembled. And, as will be seen in section 4.3.2, ULT as the end goal of RFID in semiconductor manufacturing will have tremendous benefits.

4.1.1.2 WIP

Work-in-progress typically refers to product at an intermediate stage of assembly or processing within a manufacturing plant. In a semiconductor assembly plant, one refers to both the singulated dies and the assembled semiconductors in various stages as being in WIP.

4.1.1.2.1 Dies

Dies, which are the product of wafer singulation and thus form the level of aggregation below wafers, form the lowest level of traceability in semiconductor manufacturing. Because of their high value, and since each individual die has different speed and electrical power characteristics, it is very important to track and trace individual dies.

4.1.1.2.1.1 Die reels

After singulation, dies are automatically re-segregated onto separate reels, based on varying electrical and physical characteristics originally determined at wafer probe. The process at the facility segregated the good dies into up to six "buckets;" that is, six separate reels. Each reel is barcoded with a lot number and stored in a WIP area before it is reintroduced on the manufacturing floor. *Hot lots,* that is, lots that are earmarked for fast throughput through the assembly and test process due to either customer demand or engineering needs, are physically marked as "hot" with red for easy differentiation.

Because of the extremely high value of each reel (each reel can accommodate potentially hundreds of individual dies), RFID tagging for security purposes is a viable application. Using RFID in this application is an improvement over the current use of barcodes since RFID could automatically record the illicit movement of material.

4.1.1.2.1.2 Dies at unit level

Tagging and tracking dies at the unit level is one of the potential methods for unit level traceability for semiconductors. The challenges and implications of such a scenario are discussed in detail in section 4.3.3.1. For example, if die were tracked at the unit level, there would be no need to "bucket" the dies into reels as discussed above. Rather, there could exist an infinite number of buckets such that die could be assembled, tested, and marketed based on its own individual merits (i.e., it could be clocked at the highest speed possible) and thus fetch the highest price on the open market as possible.

4.1.1.2.2 Semiconductors (die on substrate)

For the purposes of this section, a semiconductor is defined as a die assembled onto a substrate. The distinction between a die and a semiconductor here is important, and not just for the change in form factor. The differences include how unit level traceability will be implemented, as well as the different levels of aggregation that pertain to each form factor.

4.1.1.2.2.1 Semiconductor tray carts

The semiconductor tray carts are those carts that house all of the semiconductor trays during WIP both in assembly and test. Because the number of tray carts on the floor can number in the high hundreds, and because the process by which they are loaded and stored is so fluid and dynamic (i.e., disorganized), locating a specific cart can be time consuming, labor intensive, and thus costly. In fact, locating tray carts through the use of RFID was one of the initial RFID projects undertaken at a semiconductor manufacturing plant.

4.1.1.2.2.2 Semiconductor trays

Semiconductor trays are often the same trays that are used for the substrates in flip-chip assemblies. Therefore, they represent an ideal opportunity for tagging within the semiconductor environment. In fact, Philips Semiconductor recently announced that they had planned to do just that.[12]

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[12] http://story.news.yahoo.com/news?tmpl=story&cid=568&e=8&u=/nm/ibm_philips_dc.

4.1.1.2.2.3 Semiconductor at unit level

As stated before, unit level traceability at the semiconductor level provides the greatest benefits, but often also the greatest challenges for the semiconductor industry. There exist at least two methods to achieve ULT within semiconductors, which are described in greater detail in section 4.3.3.

4.1.1.3 Outgoing Product

Outgoing product refers to assembled and tested semiconductors that exit the manufacturing floor and are in transit to, waiting in, or proceeding out of the outgoing warehouse. Although the warehouse shares many of the same levels of aggregation as that of the manufacturing environment (i.e., the tray level and the unit level), the different higher level of aggregation (that of the box in the warehouse versus the cart in the assembly/test area), warrant more discussion and separate categories.

4.1.1.3.1 Trolleys

Trolleys are the caged carts used to transport boxes of trays of semiconductors between the assembly facility and the warehouse. Because of the high value of their contents, they are locked during transport. There is a desire among both factory and warehouse personnel for greater traceability, both of the trolleys and their contents. Trolleys, therefore, would be an ideal candidate not just as an object to be tagged but also as a reader, as explored in section 3.4.2.

4.1.1.3.2 Boxes

The next sublevel of aggregation is that of the shipping box. This is analogous to case-level tagging in CPG. Although semiconductor shipping boxes are unique to each manufacturer, their function is the same: to hold trays of semiconductors for delivery to end customers. At the semiconductor manufacturer studied, shipping boxes were designed to carry up to two fourteen trays divided into two side by side stacks of seven trays.

4.1.1.3.3 Trays

Here again, trays are the lowest level of aggregation above that of the unit level. And these are the same trays used throughout the manufacturing process as described above, because of their use as substrate trays prior to the manufacturing process.

Because of the ways trays are stacked and currently packaged within a box, however, the reading of RFID tags on the trays during shipping and/or receiving is problematic. First, because each tray carries an effective sheet of semiconductors, the RFID tag cannot be placed on either the top or the bottom face of the tray. Even if the tag were placed on the bottom of the tray, only the bottom tray could be hoped to be read if the trays were stacked.

The alternative, therefore, is to place the tag on one of the four edge-sides of the tray. However, there are problems associated with this proposed solution as well. One problem is that since the trays are stacked in two piles side by side by side by side, other trays would shield the long edges of the tray at least half the time. Alternatively, if the trays were tagged on the shorter sides, these ends would be facing the wrong direction half of the time and would require multiple readers situated at opposite ends to ensure proper reads.

And finally, many semiconductor manufacturers use vacuum-sealed metallized Mylar bags for both anti-static and anti-humidity protection. These metallic bags will have to be changed to non-metallic bags, Mylar or otherwise, in order to allow for the penetration of RFID signals and the tracking of trays within boxes.

4.1.1.3.4 Unit level

Again, because of the difficulties listed above with regards to reading tags on stacked trays, it is highly unlikely that one would be able to read tags on specific semiconductors, unless the trays themselves acted as readers. Therefore, ULT at the shipped semiconductor level is not plausible until the trays are unpacked from the boxes and the Mylar bags removed..

4.1.1.4 Observations

Throughout the above exercise of classifying objects within the manufacturing space, and identifying the different levels of aggregation at which they could be tracked, it is noteworthy that there are potential opportunities that exist across all three dimensions of the manufacturing space defined in this section. For example, it is important to realize that the substrate trays used for incoming product are the same WIP trays within the manufacturing plant and are the same trays that house the outgoing product. This would indicate that perhaps substrate trays

Additionally, since product is combined and assembled at different stages, what one tracks and where one tracks it can have important ramifications. For example, as noted above, the tracking of substrates at the unit level, although seemingly impractical in and of itself because of the non-uniqueness of individual substrates and their extremely low value, might enable one to eventually track the assembled semiconductor once the die is attached, giving rise to unit level traceability at the semiconductor level.

4.1.2 Reader paradigms

RFID was originally developed as a barcode replacement technology with one primary physical advantage over barcodes: RFID reads do not require line-of-sight. By itself, this advantage promises claims of higher accuracy, faster read rates, longer ranges, and simplified material handling. In addition, however, this one advantage changes the paradigm for how reads can be obtained. In the past, in order to read a barcode, the barcoded item or the barcode reader had to move relative to each other. That is, either the item moved with respect to a stationary infrared barcode scanner, or a mobile scanner moved with respect to a stationary item. This type of read is referred to in this paper as a *gateway* read. That is, the tagged item and the gateway must move relative to each other in order to perform a read. The difference

This is no longer the case. With RFID, one is able to read the location of an item without the movement of either the reader or the tagged item. This is referred to in this paper as a *shelf* application. Like the gateway applications, the shelf applications can be further subdivided by the mobility of the reader, be it fixed or mobile. Table 4 shows the four reader paradigms and their relation to one another. What follows is a description that provides more detail about each paradigm and offers examples in both semiconductor manufacturing and the outside world.

		Reader Characteristics	
		Fixed	Mobile
Application Characteristics	Gateway	**Barcode/Magnetic Strip Replacement** • Retail Checkout • Shipping/Receiving • Passenger Tracking • Baggage Handling • Package Tracking	**Handheld Readers** • iGlove • Find-It Flashlight (Handheld wireless barcode readers exist today and are in wide use in warehouses, but handheld RFID demonstrates more ease and functionality)
	Shelf	**Real-Time Inventory** • Retail Shelves/Racks • Warehouse Bins • Mailboxes • Household Applications (food, medicine, clothing, etc.) • Manufacturing Applications (ovens, washers, etc.)	**Real-Time Location** • Shopping Cart • Warehouse Trolley • WIP Carts • Sea Containers • Delivery Trucks/Trailers • Any mobile "shelf" with self-location abilities

Table 4 RFID Use Cases

4.1.2.1 Fixed Gateway

The fixed gateway is the most prevalent use for current barcode technologies and forms our first paradigm for RFID applications. In fact, since RFID is most often looked at to supplant barcodes, this is currently the most prevalent paradigm for RFID. In this paradigm, the reader is fixed and the item is moved past the reader in such a way as to register a read.

4.1.2.1.1 General examples

The most tangible example of the fixed gateway is a retail checkout counter, where barcoded items pass a checkpoint. Another common example is the shipping and/or receiving dock where pallets or cases are recorded upon entry or exit. An RFID example is the Boston Marathon, where runners are tracked at discrete points on their 26.2 mile journey.

4.1.2.1.2 Examples in semiconductor manufacturing

Fixed gateway examples in semiconductor manufacturing mirror those of the outside world. Shipping and receiving is the primary example, but essentially any situation in which a barcode is read as material is moved past a fixed point suffices. The entry of a wafer into the preprocessing machines before singulation, or the reading of reels of capacitors before being loaded onto machines in the assembly process, are fixed gateway examples.

4.1.2.1.3 Observations

The fixed gateway paradigm inherits many of the limitations from the barcoded world.

1) The direction of movement is ambiguous and must be assumed. Even though an item has passed a specific point, there is no certainty as to which direction the item traveled. In the retail checkout example, one must assume that the item(s) were once destined to leave the store premises. In the semiconductor manufacturing example, one must assume that items scanned in the receiving dock are being received from vendors, and items scanned at the shipping dock are bound for customers. The only way in which to overcome this ambiguity within the paradigm is to set up two checkpoints in close proximity to one another (as is done in the Boston Marathon). Only paired, sequential, and timed reads can unambiguously provide the direction of movement of the tagged item.

2) The fixed gateway paradigm assumes flawless reads for all items that pass the threshold. Unfortunately, this assumption does not always hold. The tracking of videos at a video store is a case in point. Store procedure requires that all videos are scanned as they exit or enter a store. In the perfect world without shrinkage or checkout/check-in mistakes, there would be no need for

inventory checks. Yet, on a regular basis, inventory checks are made to correct the database errors resulting from gateway misreads or oversights.

4.1.2.2 Mobile Gateway

The mobile gateway is similar to the fixed gateway in the sense that the tagged object and the reader must still move with respect to each other. The difference is that in this case the reader is non-stationary but the object can be stationary. In other words, a mobile (and often, but not necessarily, handheld and wireless) reader moves with respect to the tagged item.

4.1.2.2.1 General examples

The mobile gateway is most prevalent today in warehouse inventory applications, where handheld, and often wireless barcode readers are used upon placing or picking or inventory checks. Another common example is that of package tracking, as applied by UPS or Federal Express. At FedEx, for example, the truck driver uses a handheld barcode reader to register all picked-up and delivered items.

4.1.2.2.2 Examples in semiconductor manufacturing

One example for the mobile gateway attempted in semiconductor manufacturing is that of the iGlove, which is essentially a handheld RFID reader in the form factor of a glove that communicates to a base station via an alternate radio frequency. The actual application it was tested for involved automatically identifying capacitor reels handled by operators, with the goal of reducing excursions in manufacturing. This application and the associated tests are described in more detail in 4.2.1.2.

There are a myriad of other potential applications for the iGlove within the semiconductor assembly plant. Many of them, including the inventorying of items, mirror those of the outside world. For example, because of the large number of servers required in such a complex computing environment, and because of the interdepartmental structure of the service, the server room in a semiconductor manufacturing plant has the potential to fall into disarray. RFID-tagged servers and other high-value components within the server room, coupled with handheld RFID readers such as the iGlove, would permit quick and easy inventory checks for at least two reasons. First, with ever-smaller servers with more limited space onto which to place a barcode, an RFID tag might be more easily applied and read. Second, because of the ability of an RFID tag to be written to, more information about a particular server could be tracked (and changed) on the server itself without having to rely on a shared database among different organizations.

4.1.2.2.3 Observations

Just as handheld barcode readers opened up applications for product tracking and tracing, handheld RFID readers open up the world for RFID applications. But the new and unique applications for RFID are more far-reaching than their barcode cousins. For instance, the inventorying of items has the potential to be greatly sped up with the use of handheld RFID, since the RFID reader does not need to be aligned with the tag.

RFID handheld readers represent an economical way to introduce RFID into warehouse inventory systems, because they can directly replace existing barcoded systems with little capital outlay. That is, although the number of tags needed might remain the same when compared to other reader paradigms, the number of readers needed is drastically reduced. Only one reader per operator would be required as opposed to one reader per shelf which would be required for each of the next two paradigms. The tradeoff, however, is in increased labor costs since the handheld reader presupposes that an operator is doing the handholding.

Also, a problem not yet discussed with regards to handheld or mobile systems is the need for an accompanying mobile power supply. The charging and maintenance of batteries adds complexity to any process or system. Additionally, many mobile systems are purposely designed and engineered in order to preserve battery life. Unfortunately, reducing the power of an RFID system dramatically reduces its range, and thus, its functionality. The proper design of a handheld RFID system must make this tradeoff appropriately.

4.1.2.3 Fixed Shelf

The fixed shelf represents the most important paradigm shift in RFID reading techniques because it takes advantage of the primary benefit of RFID. Unlike barcodes, RFID does not require either the reader or the tag to move with respect to each other. The implications of this are far reaching. For example, the contents of an entire shelf could be inventoried with the press of a button, with no human intervention.

4.1.2.3.1 General examples

Retail shelves and inventory positions are the two supply chain applications most often cited for fixed shelf RFID applications. The applications within the consumer's home at the extreme end of the supply chain are as far reaching as the futurist's imagination. Within the home, for example, a refrigerator could query its contents for automatic replenishment, a medicine cabinet could track its contents for reasons of safety, and the washing machine could automatically wash its contents with self-awareness of what is inside.

4.1.2.3.2 Examples in semiconductor manufacturing

Aside from the potential examples that semiconductor manufacturing shares with the rest of the world (primarily warehousing), this paper discusses two fixed shelf examples as proposed solutions for the Die Side Capacitor Anti-Mixing problem already described.

4.1.2.3.3 Observations

The biggest initial hurdle in the implementation of fixed shelves for RFID applications is the high investment cost. The thousands or tens of thousands of inventory positions within large modern warehouses would require thousands or tens of thousands of readers deployed at every position. This one-for-one requirement also makes the reading of retail store shelves costly, and beyond the reach of most retailers.

The other hurdle is technical. In order for RFID shelf technology to work properly, the shelves must be designed so that the shelf reads only the items on that particular shelf, not the items on adjacent ones. This problem is only beginning to be fully analyzed at the Auto-ID Labs and in various field trials in both the United States and Europe.

4.1.2.4 Mobile Shelf

The mobile shelf can be described as the intersection of the fixed shelf and the mobile gateway, since it shares aspects of both paradigms. Essentially, it is an RFID equipped "shelf" that benefits from all of the advantages of mobility. Again, like the fixed shelves, there is no analog in the barcode world because of barcoding's line-of-sight limitation.

4.1.2.4.1 General examples

Any mobile storage device has the potential to be a mobile shelf. Sea containers, trailers, delivery trucks, etc. all have the potential to one day inventory all of their own contents on demand. The difference between these applications and the fixed shelf is obviously that these "shelves" are mobile and can thus be tracked themselves at a higher level of aggregation.

4.1.2.4.2 Examples in semiconductor manufacturing

One potential application described in Section 4.2.2 below is that of the "Smart Trolley." Essentially, it would involve the caged trolley used for the transport of boxes of semiconductors to act as a reader to query its contents at any time during loading/unloading or transport between the assembly plant and the warehouse. Essentially, it would be a "smart shelf" on wheels.

4.1.2.4.3 Observations

The mobile shelf can be thought of as the tracking of multiple levels of aggregation simultaneously. As in the example in semiconductor manufacturing above, the trays of semiconductors are tracked by the carts, which act as mobile readers which are themselves shelves. But the carts can (and will) be themselves tracked. For example, trays could one day be tagged and tracked by the WIP carts on which they reside. But the WIP cart, acting as a reader, could itself be tagged and tracked on the warehouse floor. One can even postulate that another level of aggregation (in the opposite direction) is also possible and plausible. The trays themselves could one day act as mobile readers that inventory the individual semiconductors that they carry.

Mobile shelves inherit all of the technical and logistical difficulties of both the mobile gateways and the fixed shelves. First and foremost, similar to the mobile gateways, a source of power is problematic. But the problem of battery life is compounded by the fact that the shelves will generally require more energy to inventory its contents due to the longer ranges required.

Second, the problems associated with fixed shelves are only compounded here. Whereas in a fixed shelf there exists the problem of reading what is on the desired shelf *and only* what is on that shelf and no other, a mobile shelf has the problem of entering and exiting electromagnetic fields either randomly or those created by other mobile shelves.

4.2 Process Improvement in Semiconductor Manufacturing

In order to gain a practical perspective on the possibility of using RFID to improve semiconductor manufacturing, specific challenges within the manufacturing process were identified in conjunction with a major manufacturer of semiconductors. In this effort, opportunities were identified for the application of RFID, and details of the application were brainstormed. Two cases were selected for further investigation, termed the "deep dives." Information on the chosen cases, details of the investigation, and observations are described below.

4.2.1 Deep Dive 1: DSCAM

DSCAM is short for "die-side capacitor anti-mixing," which is an instance of the more general anti-mixing challenge in manufacturing. An anti-mixing event occurs in a flexible manufacturing line when the model/specification of the work-in-process passing through the line changes, necessitating a change in the components added to the work. Addition of incorrect components requires re-work of the piece or, worse, renders it unusable.

In the DSCAM challenge, the changing specification relates to different performance levels of chips, and the components are capacitors to be attached to the work. In this process, the chip is attached to a substrate, a precision printed circuit board. Depending on the properties of the chip measured at Probe, a different "recipe" of capacitors must also be attached to the substrate by a high-speed component placement machine. These capacitors, barely larger than a grain of sand, are packaged on plastic tape and wound onto reels, similar to recording-tape reels. The reels are loaded onto a special carrier by a human operator; the carrier is ultimately attached to the component placement machine. The machine has 24 reel slots, closely spaced. For a given recipe, all reels must be loaded into the machine, but not all the loaded reels' capacitors are necessarily part of the recipe. The machine's computerized controller must "understand" what values of capacitor are loaded, and into which slot they are loaded. Based on its understanding of the currently-loaded components, the controller directs placement of capacitors.

The importance of correctly loading the reels and communicating the information to the controller should not be underestimated. Because the operation is highly automated once the reels have been loaded, the process is typically allowed to run unsupervised for significant periods of time. Consequently, if an error is made, hundreds of parts may pass through the process before the error is recognized. Due to the details of the process, re-work is not a viable option, meaning that incorrectly manufactured parts are scrapped. Depending on the sunk costs of the work-in-process, this can represent thousands or hundreds of thousands of dollars' worth of lost inventory.

4.2.1.1 Current situation: barcode scanning

Under the current process, operators first visually verify, by reading the labeling on the reels, that they have chosen the correct product. The operator then uses a barcode scanner to scan the barcodes on the reel, and to scan a barcode on a card at the component machine representing the slot being replenished. The equipment controller, with which the barcode scanner communicates, can then verify the appropriateness of the component/slot combination.

Although this system does provide for more reliable operation by allowing for verification by the equipment controller, it is still susceptible to human error. For example, a different slot code may be scanned on the card at the machine from the slot into which the reel is actually loaded, giving the machine a false impression of the arrangement of capacitor values. Documented failures of the process under the barcode system do exist, implying the potential for improvement.

4.2.1.2 iGlove solution

The iGlove, the design and construction of which was outlined in section 3.4.1 above, was proposed as a possible solution to this challenge. Through experimentation with the iGlove, it was hoped that a better solution might be found to the DSCAM challenge. Either one or both of the following gains was pursued: a solution that fit more naturally into the operator's movements and routine and therefore could be accomplished more quickly and easily, and/or a solution that was more reliable in terms of guaranteeing that anti-mixing was achieved.

Use of the iGlove in this context was originally felt to be a good fit, because it was thought that some of the limitations of the glove could become strengths. The chief example of this is the limitation on range of the 13.56 MHz reader. In this case, it was felt that the short range could help the system be more "sure" of which reel or which carrier the operator was handling. This specificity is important where there may be many different carriers and reels. A longer-range reader, on the other hand, would likely read the tags on every carrier and every reel at the workstation, making it hard for the system to determine which carrier was being handled, and which reel loaded.

In investigating the application of this solution to DSCAM, the research team attempted to formulate a series of process steps compatible with the glove that would accomplish the goals of the challenge. Also included was the formulation and prototyping of a Windows-based interface application to test the behavior of the reader and its hypothetical interaction with the base station.

Briefly, the process was proposed to work in concert with pre-tagged reels and carriers, together with a method of discerning the active slot in the component machine. One such method involved the use of an indicator attached to the slot, such as a microswitch that activated upon removal/replacement of the carrier. Another possibility involved the interface application's keeping a mini-inventory of the carriers and, based on the tag ID of the carrier being held, infers the slot being changed. Using a database that stores information about the components on the reel, the base-station computer determines whether the correct reel is being used/installed.

4.2.1.3 Single fixed reader solution

An alternative to the solution described and tested above involved installing a single fixed reader at the end of the row of capacitor reels. The concept was that if a reader could read all 24 reels simultaneously, it could determine whenever a single capacitor reel was removed or introduced. This is akin to the fixed shelf solution described in 4.1.2.3.

Unfortunately, there were many technical issues related to this solution. First, it was doubtful that a reader could read through all 24 reels, because of the high density and high metal content of the capacitors. Even if a reader were hypothetically powerful enough, or somehow uniquely configured, to read through all 24 capacitor reels, the varying density of the individual reels could potentially present additional problems. If a reader were tuned at maximum power but the number of capacitor reels or the density in each reel were dramatically reduced as a matter of course, it is possible that the reader would be too powerful and might erroneously read the reels of an adjacent machine.

Second, because of the design of the current machine onto which the reels are loaded, only about half of the face of the reel is visible at any one time. The other half of the reel is covered by the metal carrier in which the reel sits.

And finally, although the single reader could theoretically infer that a reel was removed or that a new reel was introduced simply from taking multiple inventory counts, the reader could not determine by itself which reel position was affected. Like in the iGlove solution described in 4.2.1.2, the single fixed reader would have to work in concert with a method of discerning the active slot in the component machine. Even then, it would have to assume that only one capacitor reel was removed and/or loaded at a time.

4.2.1.4 Multiple fixed readers solution

An alternative to overcome the limitations to the single fixed reader solution is to instead imbed multiple readers or antennas, one at each capacitor reel location. This is akin to simply increasing the granularity and pinpointing the location of the reels. The multiple fixed reader solution solves two of the problems of the single reader simultaneously. First, by reading precise locations it mitigates ambiguity. Second, the solution does not rely on reading *through* high metal content reels of varying density.

A significant technical challenge with this solution, also noted in the single-reader solution above, is the inability to read the reels half the time due to the metal carrier in which they are housed. Two methods of addressing this challenge are to either redesign the machine with RF transparent materials, such as plastic, or to place multiple tags on each reel such that at least one tag is "visible" to the RF reader at any one time. This second method would involve either placing two tags with two different unique identifiers (UIDs) on the same reel and assigning them both to the reel, or somehow copying the UID of one tag and duplicating it on the alternate tag.

The main limitation for this multiple reader solution, however, is cost. Although the iGlove solution (and, of course, the single fixed-reader solution) would require only one RFID reader, this solution could require twenty-four per machine. If one operator (and thus one glove) could cover the operation of four machines, it is plausible that the multi reader solution could increase the cost by two orders of magnitude. Even assuming it is possible to implement this solution using multiple antenna inputs to a single reader, the implementation is undoubtedly more costly and difficult than a single reader would be.

4.2.1.5 Observations/lessons learned

One of the most important lessons learned in attempting to address the DSCAM challenge using RFID is that position/location information is very important in the manufacturing environment, and that current RFID implementations do not present robust solutions for determining position/location. Most current RFID systems excel at determining that a specific object is "nearby" (where the maximum distance representing nearness is a parameter determined by the range for reads under extant conditions), but are not capable of determining with any accuracy in which direction relative to the reader the object is located, or exactly how far away.

As noted above, every solution required some method of deducing the location of the manipulated reel carrier (that is, the active slot). In the case of the iGlove solution, it was hoped that the specific nature of the user's interaction with the environment and the low range of the reader would help provide the system with the positional information necessary. Although this promise may well prove workable, it seemed clear from the implementation investigations undertaken with the assistance of the research team at the semiconductor-manufacturing partner that the challenge in a system like this would be in helping the user-interface application infer continuity of physical objects through persistence of tag reads, knowledge of current state, etc. Failing this, it would be necessary to use other solutions, such as the microswitch approach, to allow the system to "know" positional information. The multi-reader solution took a different approach to specificity, using individual readers or antennas to determine position; the single reader solution again required the use of microswitches or some similar approach to solve the location challenge.

Although interesting solutions are in the works for combining a smart RFID device with the ability to determine location with reasonable accuracy, it is telling that one of the most well-developed such solutions, the MIT Laboratory for Computer Science's Cricket prototype, uses ultrasonic beacons and detectors for the location portion of the functionality.[13] Although it may be possible to develop RFID-only solutions for use indoors that are capable of determining positional data, these solutions will have to overcome hurdles like multipath effects (where signals are reflected off surrounding surfaces) and electromagnetic interference from equipment in the building.

Another important consideration when implementing RFID in the manufacturing space that revealed itself during these investigations is helping the interface application to understand persistence. Human beings take it as a matter of course based on years of real-world experience that physical objects cannot disappear and reappear, and we have many senses to help us determine the presence or absence of an object. For an RFID application, however, it has only the sometimes-unreliable read of a specific tag to detect an object. The application must then recognize, in the context of the operating environment, what the presence of the tagged object means. For example, if a reader were placed at the carrier loading station for the die-side capacitors, the detection for a large period of time (a few minutes, say) of the tag on a carrier and reel might allow the application to deduce that the reel was loaded onto the carrier. Upon its return to the machine, insertion into the slot would allow the application to verify correctness of the component type.

4.2.2 Deep Dive 2: Smart Carts

Another test application in semiconductor manufacturing is the use of RFID to track boxes of semiconductors that pass from the assembly and test area to the warehouse. These facilities are always co-located and often adjacent to one another, but they are logistically different entities to and from which product must be transferred.

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[13] MIT Laboratory for Computer Science, "The Cricket Indoor Location System: An NMS Project @ MIT LCS," http://nms.lcs.mit.edu/projects/cricket/.

4.2.2.1 Current situation/analysis of problem

Today, the boxes are currently tracked with barcodes in order to increase security and ensure delivery from one location to the other. However, there is no tracking in transit. That is, only the gateway information is recorded (i.e., the boxes are scanned as they enter the cart and they are scanned upon exit to the cart). One big limitation in this scenario is that the process is operator dependant, and thus due to errors. For example, a misread or a non read upon entry or exit to the cart, or a failure to read the barcode on the cart itself, will render the data captured useless and has the potential to account for lost inventory in transit.

4.2.2.2 Proposed solution/analysis of solution

The current proposed solution is to equip the trolley with appropriate RFID readers in order to track the RFID tagged boxes *as they sit in the trolley.* The trolleys would in effect be "smart carts" much like the shopping carts envisioned and designed for the future RFID-equipped supermarket. This smart trolley is currently in early stages of development at at least one semiconductor manufacturer, but there are many obstacles that must be overcome.

The first realization that must be made is that this trolley, by definition, fits into the category of "mobile shelf", as described in 4.1.2.4. Early thinking erroneously envisioned a gateway design by which the tagged boxes were read upon entry or exit into the trolley. However, this leads to the ambiguity with regards to direction of movement as described in 4.1.2.1, and it does not ensure real time location.

The second realization is that each shelf on the current metal trolley acts as an effective Faraday's cage. That is, RF signals cannot penetrate the shelf from the exterior of the trolley, and each shelf would be required to have its own reader or antenna. This design would be akin to the current ideas regarding smart shelves in the retail space, where every stocking space has at least one reader not only to increase the granularity of the location but also to ensure reads between the metal shelves. Aside from redesigning the cart completely out of plastic, the only other solution is for careful and deliberate antennae placement, which leads us into our next issue.

Placement of the reader antennae and the tags on the boxes is the next obstacle. Because of the density of the boxes as described in section 4.1.1.3.2, it is unlikely that a read would register on stacked boxes. Therefore, the boxes could not be stacked more than one high and the reader's antennas would have to reside on either the top or the bottom of each shelf.

And finally, because the trolley proposed to be a mobile reader, the power source is a major point of concern. The higher the power of the reader, the longer its range and the greater its accuracy, so tuning and maintaining the power available would be both environment and process dependent. Furthermore, batteries are costly and their recharging and can be cumbersome and labor intensive. The power design will definitely be a major design problem with success dependent on the intuition of the designer.

4.3 Unit-Level Traceability (ULT) in Semiconductor Manufacturing

4.3.1 Overview

Unit Level Traceability (ULT), that is, the tagging and tracking of items at the smallest aggregate level, is the purported end goal of many RFID initiatives, from the Department of Defense to Wal-Mart. The DOD hopes to use RFID to one day achieve unit level traceability to track all of the tens of thousands of parts on the bill of materials for such complex items as weapons delivery systems. Wal-Mart would like ULT at the item level to reduce shrinkage from the shelf and eliminate out-of-stock OOS situations. The semiconductor industry would like ULT for many reasons, both in its supply chain and its manufacturing environment.

4.3.2 Implications of ULT

The real benefits of RFID for the semiconductor industry will not be realized until there is true unit level traceability, that is, traceability at the die and/or part level. When this occurs, all of the benefits of the forward and backward supply chain that are derived from a serialized part will become immediately available. Additionally, manufacturing processes can be redesigned, optimized, and streamlined in now unimaginable ways.

Unit level traceability (whether or not implemented with RFID) can have enormous impact on the supply chain of semiconductors in the future. Today, generally only the part number and the lot number of a part is captured in the code silk-screened onto its package. When tied to a database, this information is often used to track approximate manufacturing date and manufacturing facility. Of course, this assumes that the parts from each lot share identical electrical and speed characteristics. This is far from the case, especially with today's high transitory counts approaching 1 billion transistors. Unit Level Traceability will provide wafer information (with a more exact build date) as well as precise wafer location, as well as probe and final test characteristics.

Theoretically, original wafer location of a die could alter the characteristics of that die. It is possible for a manufacturing defect to not be discovered until well after a part has made it into the field and sometimes to the end customer. If the above two assumption hold true (that is, if a defect in the field were traced to just a section of a wafer from a particular lot), the scope (and cost) of a recall could be greatly reduced.

For example, if an automotive semiconductor product were released with a defect that was not discovered until much later in the supply chain, say, at the subassembly, final-assembly, or even customer level, a recall might be much easier to implement with ULT. This would especially be the case if the defect were a manufacturing error that could be traced back to a particular lot, a particular wafer, or even just certain die on each wafer. There exist two possible scenarios for discovery of a defective part at the end-customer using ULT: 1) An RFID-equipped service provider could noninvasively read the serial number of a particular semiconductor within the final assembly (the car). 2) Better yet, a properly designed database linked to a manufacturing process would already know the serial number of each subassembly the defective part was built into. A separate database would be able to match the subassembly serial number to the VIN of the actual vehicle. Although the second method is by far much more convenient in a recall, either method has the potential to substantially reduce the cost of recalling defective parts on vehicles.

Among the major trends in supply-chain management is the move toward shorter product life cycles. This is especially true in the semiconductor industry as competition continues to grow and customer expectations intensify. Interestingly enough, however, is that sometimes the products in which these semiconductors are embedded have much longer life-cycles than the semiconductors themselves. This creates a product support headache for a semiconductor manufacturer (with a sixth-month product life cycle) supporting an automotive product (with an average of a 3 year life cycle). This headache is exacerbated when the semiconductor manufacturer realized that it must support the product for 10 years (the warranty life of an automobile).

The biggest difficulty stemming from the life cycle differential is the fact that semiconductor product updates are discouraged because of the support nightmare. It would be difficult if not impossible to know which release of a semiconductor would be tied to the serial number of the end product without ripping apart the product and visibly inspecting the part number and lot number on the semiconductor packaging itself. RFID would not only allow non-intrusive querying of the part within the product, but with ULT, as long the database is well-designed, maintained, and easily accessible, it would eradicate the need for the query in the first place. That is, the ePC of the semiconductor would already be tied to the serial number of the product in which it is embedded.

Another potential application of ULT is the tracking of firmware that is loaded onto a semiconductor possessing internal ROM or permanent flash memory. Rather than changing the part number of the product every time a new revision of code is released, a semiconductor manufacturer could track the released version of firmware part by part by tracking the ePC of each part upon release. This could even aid automatic firmware updates in the field, if properly managed.

An additional, albeit rather specific, use of RFID and ULT would be to embed the MAC addresses of Ethernet transceivers by way of RFID. This would enable end users to easily identify both the MAC address of the transceiver and the end product (be it Ethernet card, wireless transceiver, or computer) nonintrusively, without software or a user interface, and without even powering the computer. This specific application may only become useful if RFID were to become truly ubiquitous such that every system administrator were to possess their own reader.

4.3.3 ULT w/ RFID

Unit level traceability has the potential to be implemented with RFID, especially as RFID becomes more accepted into the semiconductor manufacturing environment. There are two very different methods with which RFID could be implemented at this level of aggregation: either on-die or off-die. Each method, as will be shown below, has its own tradeoffs with respect to the other. Although the off-die RFID might be easier to implement and thus might drive the initial push towards unit level traceability, the on-die RFID, although perhaps initially impractical, offers more utility and will provide future applications that are barely at the conceptual level today.

4.3.3.1 On-die RFID

On-die RFID, that is, the implementation of RFID by incorporating the necessary transistors into the current piece of silicon, would offer true Unit Level Traceability for the die even before singulation. This would offer easier and improved tracking of the die not just back to the particular wafer, but to the exact location of that particular die on that particular wafer. The following diagram shows portions of the chain where tracing is enabled by on-die RFID.

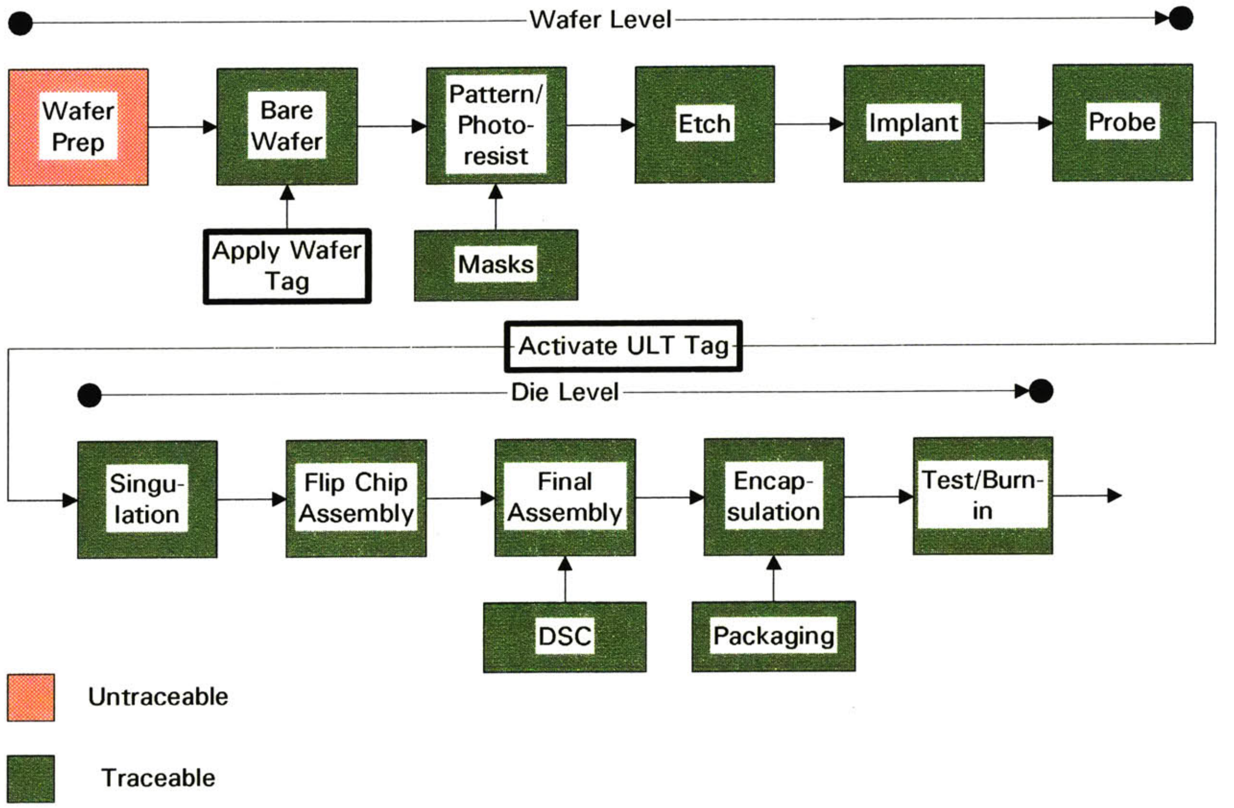

Figure 1 Traceability for On-die RFID

The technical issues in this scenario, while not necessarily insurmountable, are daunting. The largest of the technical issues is placement of the antennae. Although the additional transistor count required, and thus the required additional sized footprint of the die, would be negligible, there would be absolutely no room on a die to put an antennae without increasing the die footprint by at least on order of magnitude. Even if the antennae were to cover the entire space of the die, it would be too small by to read from or write to by conventional standards.

This brings up the next issue: If the antennae were to be that small, how would information be written to the tag, or even read from it, when the die is uncut and still on the wafer? Conventional methods of writing to a tag would make it nearly impossible to write to a tag so close to other tags. If one were to wait until after singulation in order to write the unique identification (UID) to the embedded tag, one would lose all traceability of the die to the wafer location, which was stated as one of the prime motivations for unit level traceability in the first place.

A practical work around given current technologies is to incorporate the antennae onto the substrate or other part of semiconductor's packaging, such as the cap. This leads us to our next scenario, where instead of moving simply the antennae section of the RFID chip to the packaging of the semiconductor, the entire RFID chip is moved off-die.

4.3.3.2 Off-die RFID

Given that there are so many technical hurdles for on-die RFID, an initial step to achieving unit level traceability for semiconductors is to simply tag the substrate or the other packaging (such as the cap) to which the die will eventually become associated. The diagram below shows traceable parts of the manufacturing chain with off-die RFID.

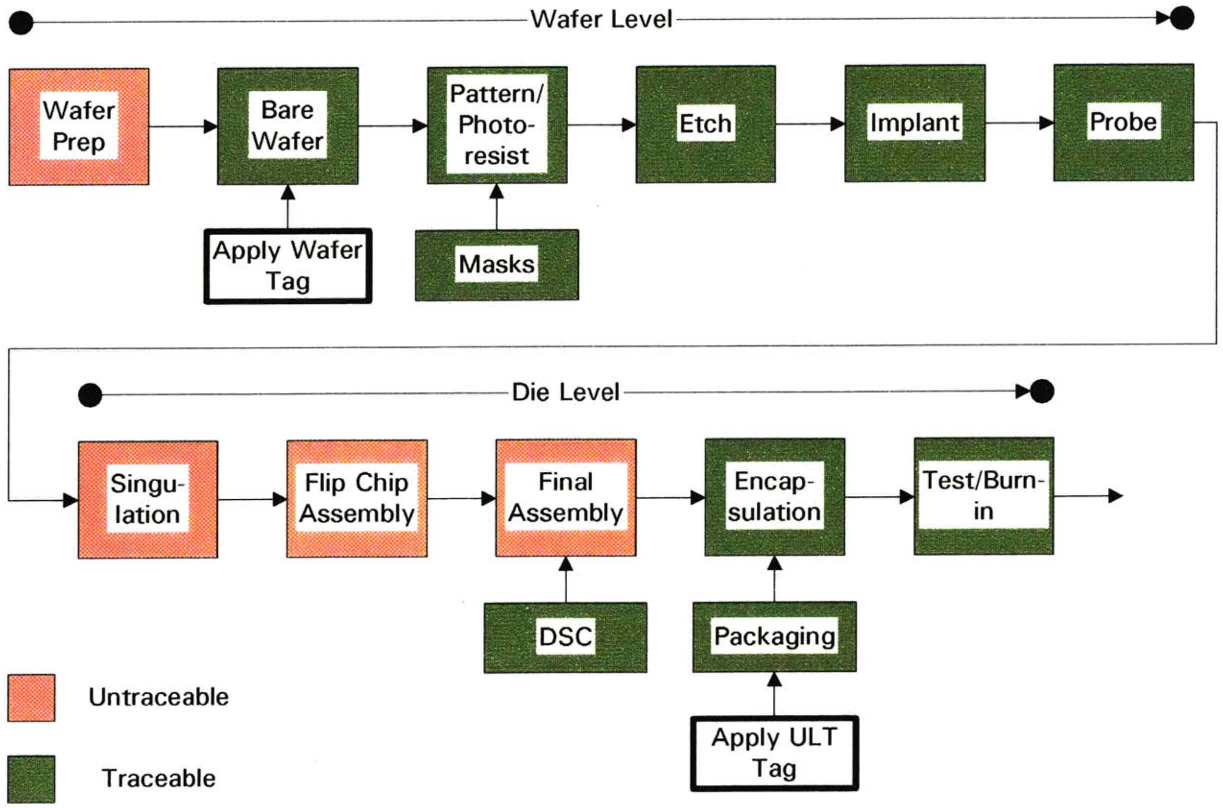

Figure 2 Traceability for Off-die RFID

The benefits of this off-die RFID are plentiful. Besides being easier to implement, the costs of such a scheme would initially be far less than that of the on-die RFID. For one, standard tags, be it ePC-compliant or not, could be affixed to the substrate or other packaging at either the supplier site or at the semiconductor assembly plant. It would not be necessary to redesign every chip in a semiconductor manufacturer's product line in order to incorporate RFID as a means for ULT.

More importantly, as noted before, many high-transistor count semiconductors may actually have enough area on the semiconductor cap or the substrate itself in order to place the entire RFID tag including the antennae. In some metal caps in use today, the antennae could even be etched onto the current metal covering.

Placing the tags on other incoming components has the added side-benefit of being able to track those specific components. However, as noted earlier, the exact value of tracking such low value components is questionable.

5 Observations and Future Research Directions

5.1 *Implications of RFID for Semiconductor Manufacturing*

In general, there seems to be promise in the continuing application of RFID in the semiconductor manufacturing environment. The current industry push into integration of RFID, particularly with the latest (300-mm wafer) toolset, in some sense represents the "low-hanging fruit" in the in-factory supply chain. Here, relationships are clear: the carrier (FOUP) is a well-defined entity, and its arrival at points in the fab or its passing of points in the material-handling system are explicitly definable events. Development of these avenues for application will undoubtedly continue; assuming that the industry moves toward unit-level traceability, the aggregate-level applications implemented in conjunction with material-handling systems may be re-tooled to work with unit-level tags, either at the wafer level or the die level. The challenge, therefore, is identifying the value of unit-level traceability, and solving the challenges associated with its implementation across the supply chain.

Equally challenging, perhaps, is the application of RFID technology in other parts of the semiconductor manufacturing environment. In the "deep dives" carried out as part of this study, it became clear that implementing RFID is not a straightforward endeavor. The choice of reader and application characteristics profoundly affects the course of the implementation. Careful thought must be given to each step of the process, and the actions carried out by operators must be anticipated and carefully accounted for. For example, as noted in the DSCAM investigation, fixed or mobile readers could be used, with specific ramifications for each choice.

While searching for candidate RFID applications within semiconductor manufacturing, two attributes of the candidate items for tagging consistently emerged: the items' value and the need to easily and positively differentiate between similar but unlike items.

Often, more expensive items were sought out in order to both absorb the cost of the technology and prevent shrinkage. This is analogous to the CPG industry, where items such as razor blades were the first to be evaluated on an item level basis, due primarily to their high cost and small item size. Another similarity to the CPG industry was the desire to initially tag items at higher levels of aggregation. This itself is done for two reasons: 1) to satisfy the above desire to tag a higher value item, and 2) because of the lowered bar with respect to technical implementation.

Additionally, the ability to unambiguously differentiate between two similar items—as in the DSCAM deep dive—provides a case in point where RFID has the potential to provide a clear advantage over the current solution by eliminating human error. Barcodes, by their very nature, require some sort of human intervention. If an operator is not physically reading a barcode with a barcode reader, he/she is often physically positioning a case or pallet directionally in order to be "automatically" read by a stationary barcode reader. RFID has the potential to reduce human input into the process and thereby reduce human error.

In the DSCAM case in particular, however, the advantages of RFID over the current process of barcode scanning were never proven. Among the problems with RFID was that its abilities, in essence, were *too great*. They often created more problems than they solved. For instance, the range and direction of the reader was difficult to control, and thus items have the potential to be unintentionally read, especially while using mobile readers.

One of the key learnings about RFID is that it has one primary advantage over the barcode: the absence of a line-of-sight requirement. Almost all other benefits of RFID—the faster read rates, the higher accuracy, the longer ranges—are all consequences of this primary advantage. An additional advantage of RFID over the barcode is the ability to write and store additional data to the tag *in situ*. Most applications that are currently under development underutilize this secondary advantage. This tendency to overlook the basic disruptive advantages of RFID led to the concluding understanding regarding RFID.

While analyzing RFID applications, one of the most common errors is to identify applications in use today that utilize barcodes. A simple replace-and-optimize strategy has been practiced throughout multiple industries including the semiconductor industry. This perspective is, perhaps, too limiting. The understanding that this is not just a better barcode but a different way of identifying products has the potential to profoundly expand the number of applications and the ways in which information is collected and utilized. Understanding, for instance, the reader paradigm shift from gateway applications to shelf applications will help broaden the range and depth of research and applications.

In general, it seems probable that RFID applications will find their way into the semiconductor factory. Interest in the technology is high, and advances in the technology are constantly being made, increasing the chances of an interested investigator identifying a suitable application of the technology.

5.2 Future Research Directions

It has been noted throughout this document that RFID, while not technically a new technology, is certainly an emerging technology. The developments of the recent past—Internet technology, standardization, miniaturization, falling tag prices, and so on—have all led to an increasing pace of innovation in RFID. This paper has examined one small part of RFID's potential, but the field is still ripe with opportunities for further investigation. A few such opportunities are touched upon below.

Although the mandate to use the iGlove as a solution to the DSCAM challenge is less than clear, in general the iGlove seems to represent a potentially valuable new way to apply RFID technology. It would seem to be worthwhile to continue development of the glove or other handheld wireless gateway applications. Feature development could continue, in terms of battery life, accompanying software, and industrial design. In addition, new uses for the glove can be devised; for example, one possible new application for the iGlove is in inventory and asset tracking in the data center. Combination of the iGlove technology with location-aware hardware such as the MIT LCS Cricket system may also yield useful new devices.

From a business and process-control standpoint, the use of RFID (particularly for unit-level traceability applications) will require substantial re-engineering of processes. For example, for ULT, the necessary implementations must be made in chip manufacturers' ERP software systems to track individual dies. Similarly, the software that controls the fab, known as *manufacturing execution software*, or MES, must also be programmed in such a way as to initiate and maintain the tracking of dies at the unit level. The specifics of these implementations, and their cost and effort implications, must be investigated to determine whether such investment is worthwhile.

For RFID to truly reach its full potential as an enabler of the efficient supply chain, application of the technology must extend beyond the four walls of the fab. The semiconductor manufacturer's suppliers and customers must also embrace the technology. This fact also provides opportunity for research, as the implications, costs, and returns of this process must be investigated more fully. In fact, this is the subject of allied research currently underway that examines one part of the supply chain, the portion that starts at the chip manufacturer's warehouse and ends at the customer's assembly floor.[14]

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[14] Duckworth.

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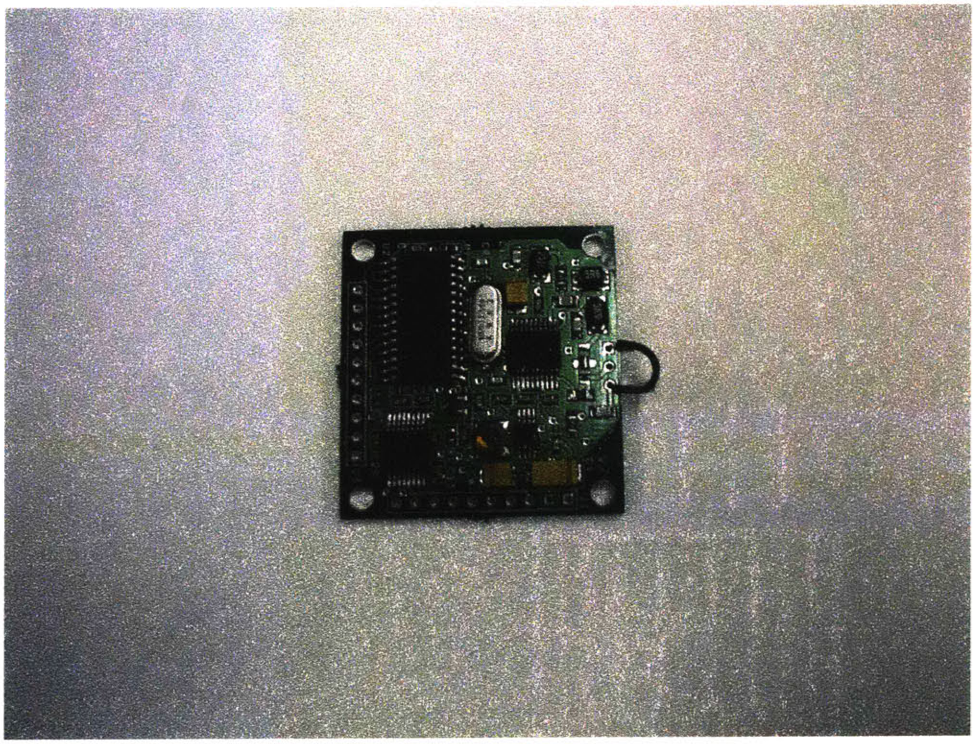
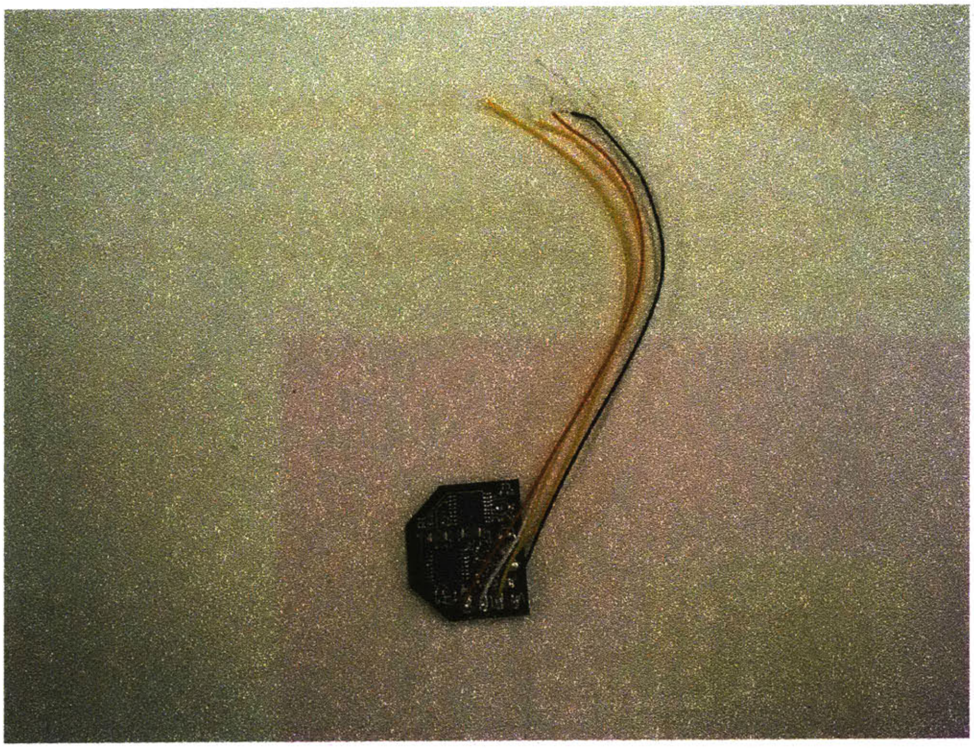
A Appendix A: iGlove Information

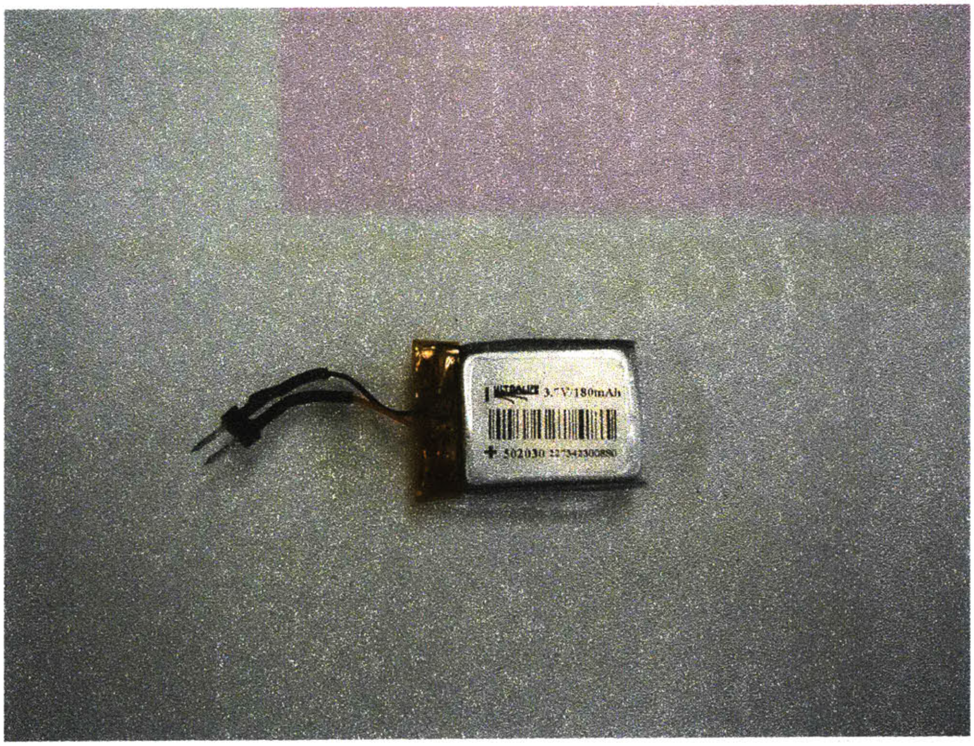
The rationale and general information about the iGlove RFID reader are contained in section 3.4.1 in the body of the paper. The photographs below depict the parts of the glove separately, and assembled into the completed reader.



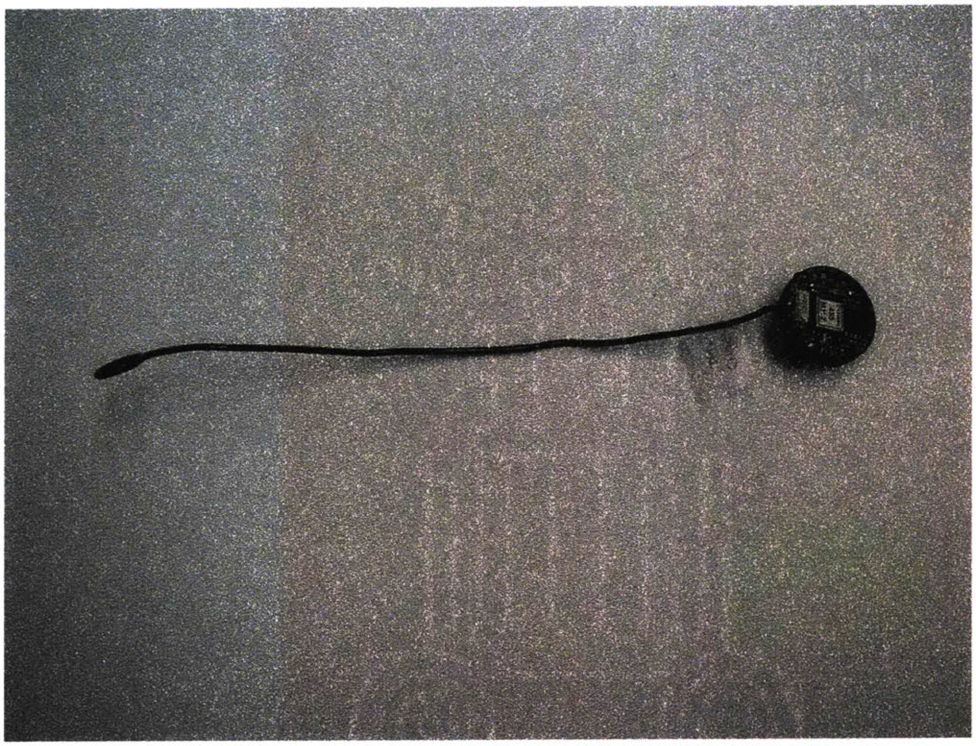
SkyeTek SkyeRead M1 portable reader/writer is a 13.56 MHz reader board, and provides the connectivity between the glove and the RFID tags.



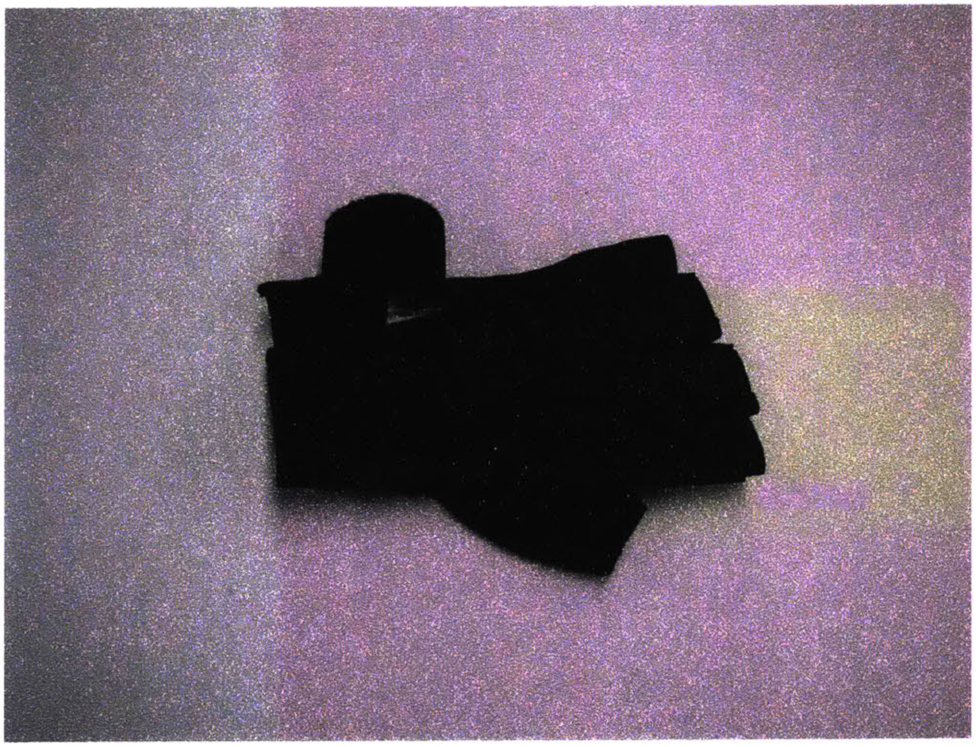
The custom logic board performs electronic signal translation between the reader and the mote, and also voltage regulation between the battery and the mote and reader.



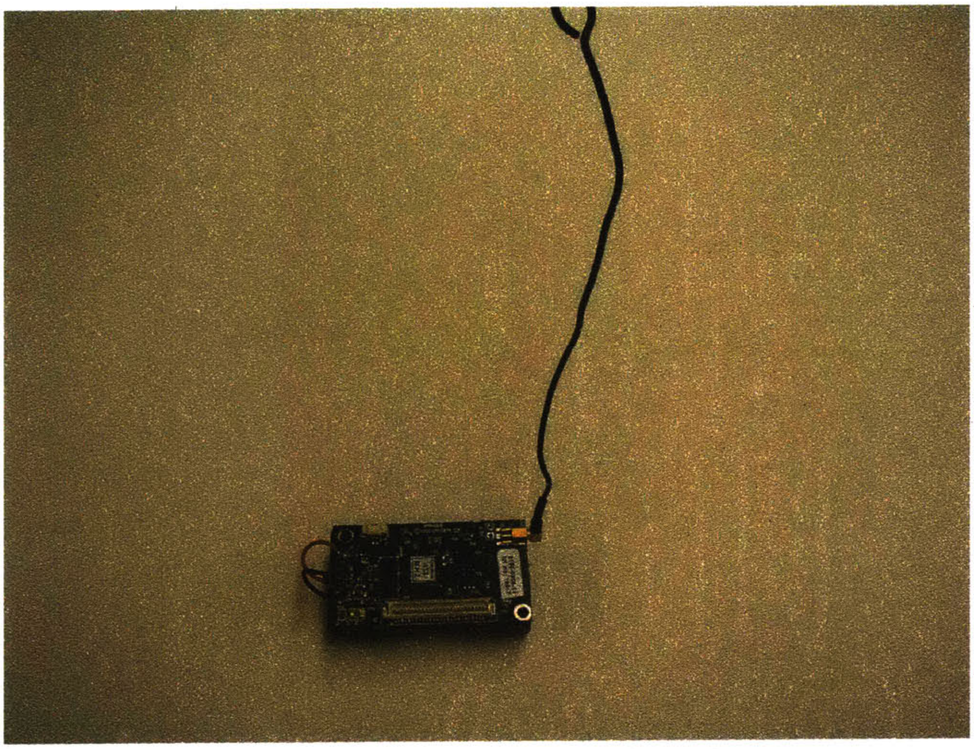
UltraLife UBC322030 Polymer rechargeable battery provides power to the components of the iGlove for approximately 4 hours.



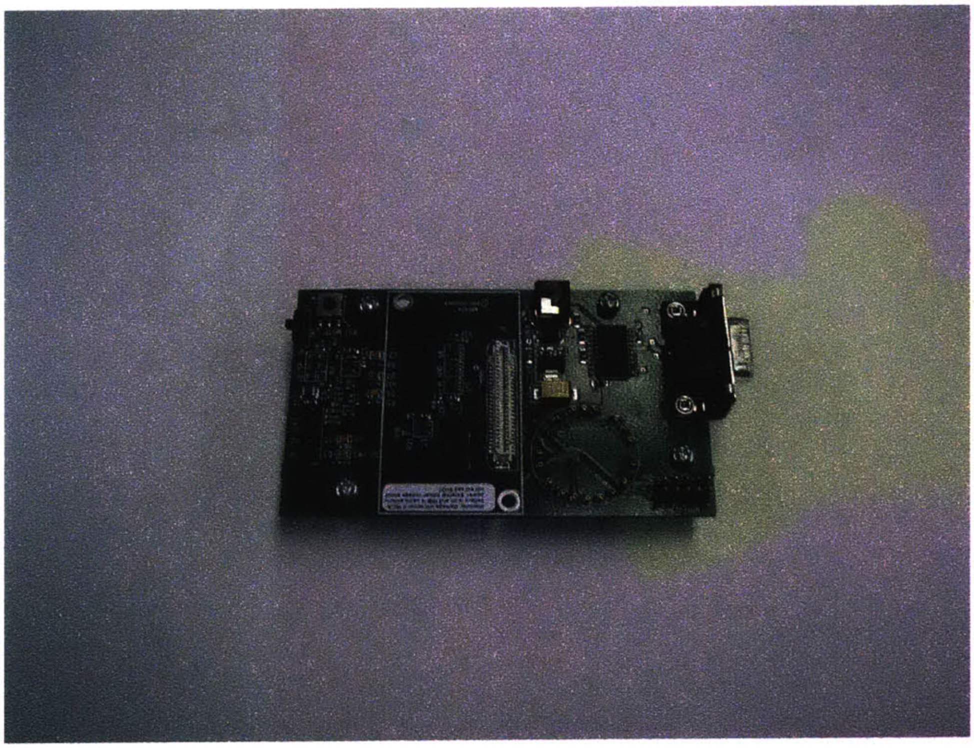
Crossbow Technology MICA2DOT mote provides wireless networking functionality to the iGlove, allowing it to connect and send its reads to the base station.



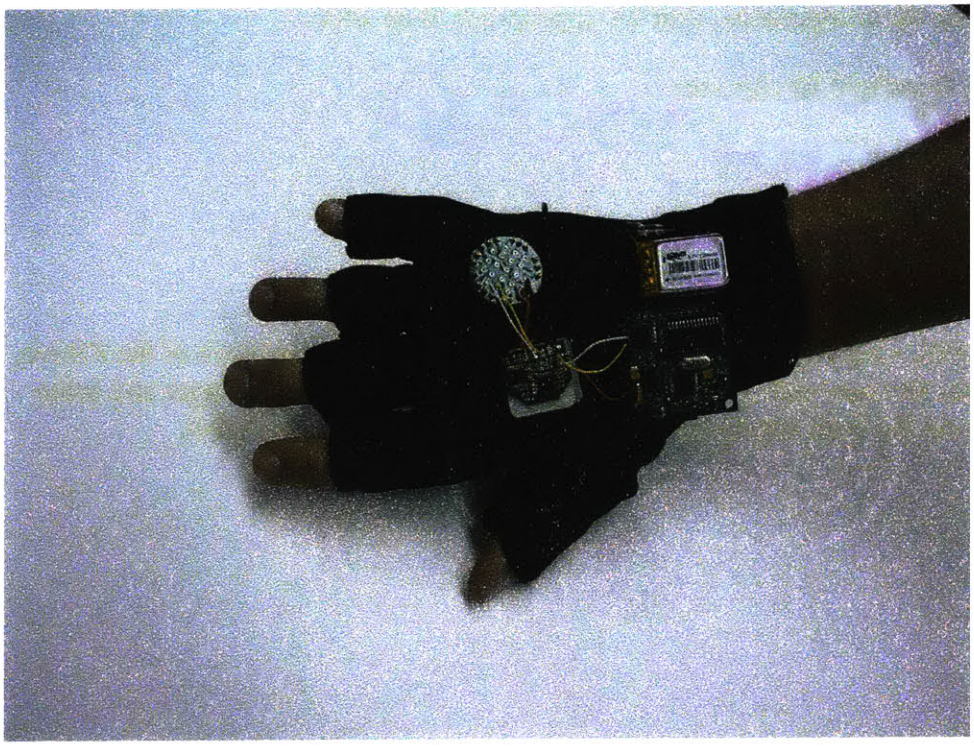
The glove is the physical platform to which the components are connected.



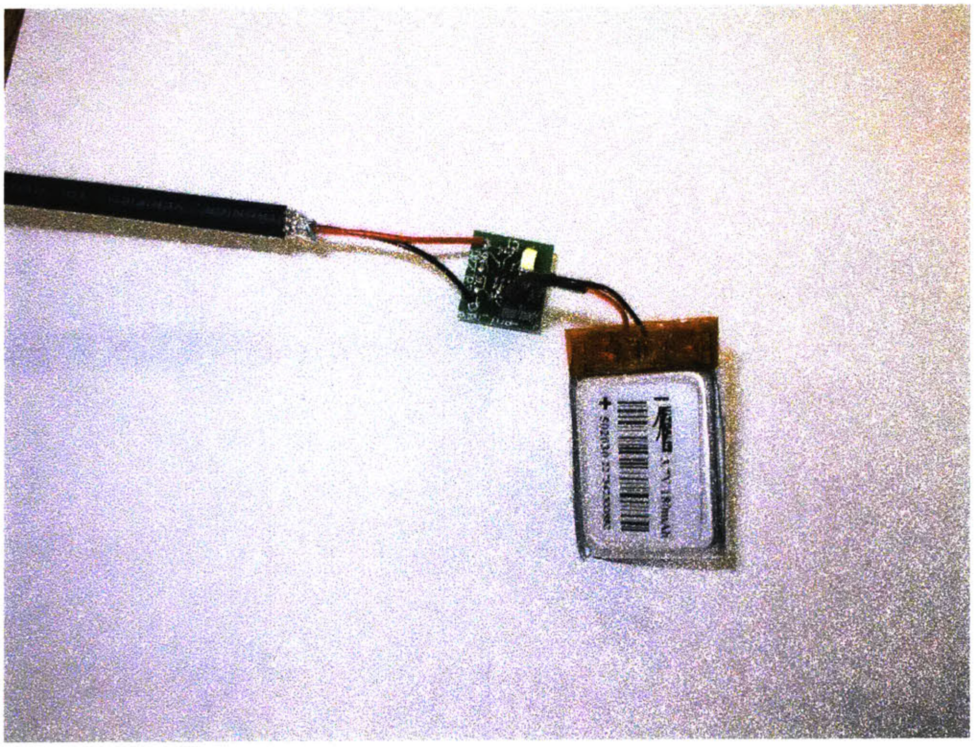
Crossbow Technology MICA2 mote acts as the receiving station, receiving signals from the MICA2DOT on-board the glove.



Crossbow Technology MIB510 gateway board connects to the base station computer via the serial port. The MIB510 provides programming functionality for the motes, and also allows the MICA2 to transmit its received signals through to the base station.



The completed iGlove.



The battery charger, fashioned from a USB interface cord, allows the battery to be recharged by plugging into a computer's standard USB port.

For more information on the components, visit the appropriate Web sites:

Intel Research–Seattle Handheld Reader site:
http://seattleweb.intel-research.net/projects/HandheldRFIDReader/

SkyeTek: http://www.skyetek.com/

Crossbow Technology: http://www.xbow.com/

UltraLife: http://www.ultralifebatteries.com/

The document on the following pages, produced in conjunction with the hardware of the iGlove, gives general guidelines for users and demonstrators of the glove. Use of the charger and setup of a terminal emulator on the base station computer for display of reads is included.

iGlove Demonstration Instructions

Purpose of document

This document describes the complete operation and settings of the iGlove demonstration, ncluding that of the battery charger, the host computer, the base station, and the glove itself.

Battery Charger Operation

Note: the charger is designed to operate on the 5V supply from any USB "large" type connector, i.e., the USB connector found on any modern laptop or desktop PC.

<u>LED indicator key:</u>
"Fast blinking light": The charger is powered, but no battery is connected.
"Solid light": The battery is charging.
"No light": The battery is charged.

<u>Directions:</u>

1) Power and turn on a computer, be it a Mac or PC, laptop or desktop.
2) Plug the charger into the USB connector of the computer.
3) Observe a fast blinking green LED on the charger. This indicates that the charger is powered.
4) Identify the positive terminal post on the charger. It is located on the very corner of the charger and is identifiable by a white silk-screened "+" sign.
5) Plug the battery pins into the charger post such that the red (positive) pin of the battery lines up to this positive terminal of the charger.
6) Observe the LED. A solid green light indicates that the battery is charging. An LED that emits no light indicates that the battery is fully charged.

Host Computer Configuration

<u>Directions:</u>

1) Connect an RS-232 Serial Port Cable to the COM port of the host computer.
2) Open a terminal emulator (such as HyperTerminal) on the correct COM port using the following settings:

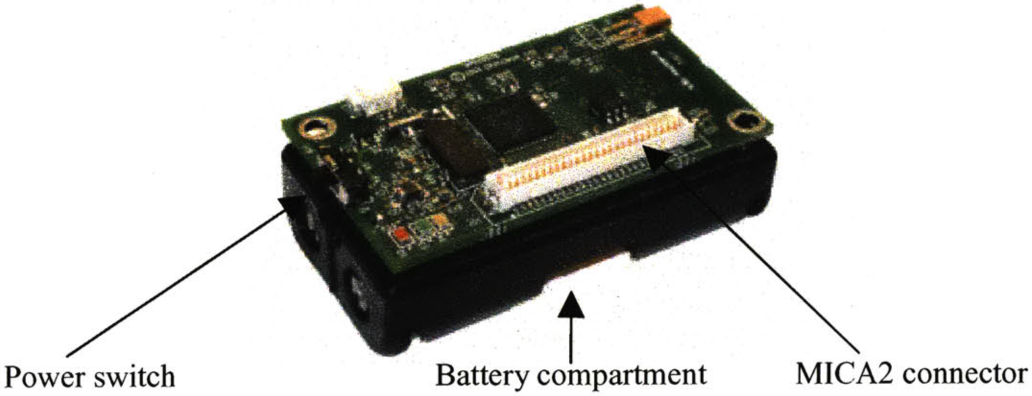
Baud rate: 19200
Flow control: None

Base Station Operation

Directions:

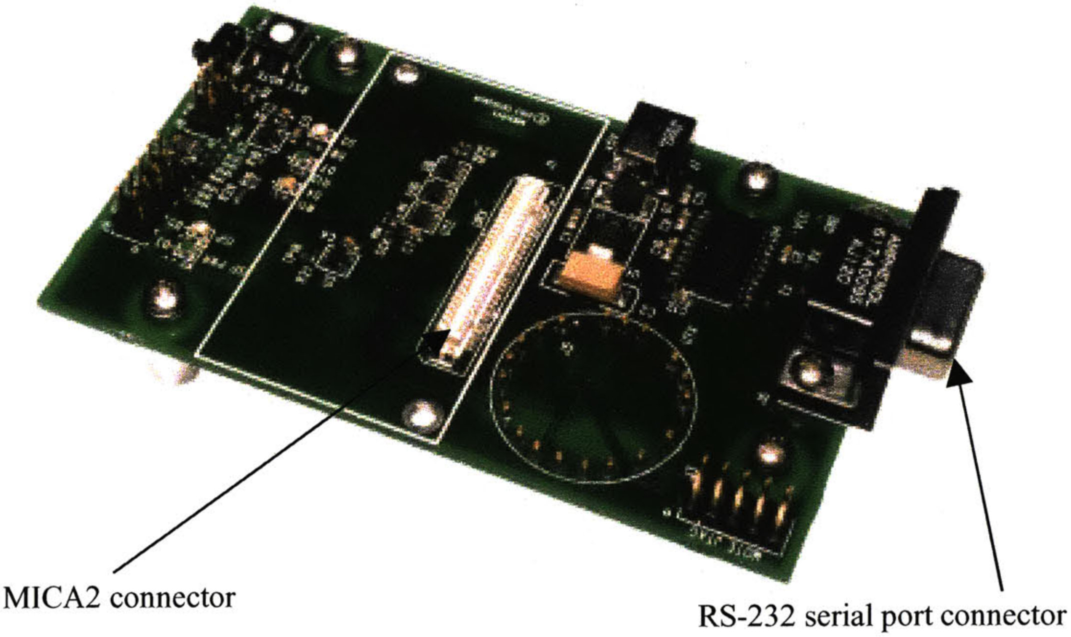
1) Place 2 AA batteries into the battery compartment of the Crossbow MICA2.
2) Plug the Crossbow MICA2 directly into the Crossbow MIB510 using the MICA2 connector.

Figure 1: Crossbow MICA2



3) Power the entire system by toggling the power switch on the Crossbow MICA2 to the “ON” position.
4) Connect the Crossbow MIB510 to the Host Computer with a Serial Port Cable.
5) DO NOT power the Crossbow MIB510 independently, except through the Crossbow MICA2.

Figure 2: Crossbow MIB510



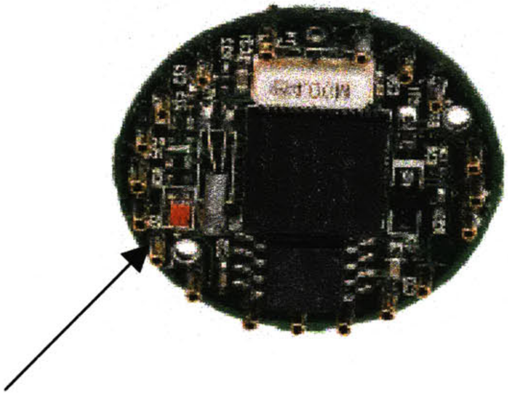
iGlove Operation

Directions:

1) Place the glove on the operator's right hand.
2) Connect a charged battery to the iGlove such that the red and black terminal posts of the battery line up to the respective red and black terminal plugs of the iGlove.

NOTE: The iGlove is now powered and operational. (No LEDs should light at this time.)

Figure 3: Crossbow MICA2DOT



Red LED

3) Keeping the palm flat (and the antennae in a plane), test the iGlove by bringing the antenna (palm) of the glove within an inch of an RFID tag.
4) Watch for the red LED to blink "ON" or "OFF". Every transition of the LED indicates a positive tag read by the RFID reader.
5) Watch the red LED on the MIB510. Every transition of the LED indicates the transmission the RFID code read from the MICA2 DOT to the MICA2.
6) Watch the terminal emulator on the host computer. Every positive read and transmission of an RFID code should be displayed on the screen.